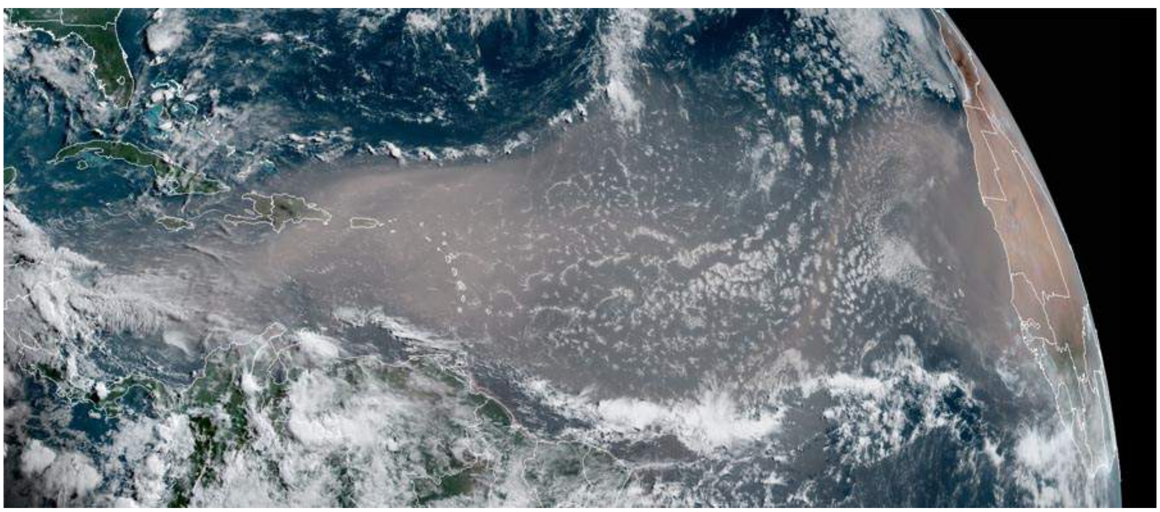
Aerosol, Cloud, Convection, and Precipitation (ACCP) Science & Applications

ACCP provides transformative three-dimensional space-based and suborbital observations of essential collocated cloud, dynamic, precipitation and aerosol processes, leading to improved predictions of weather, air quality, and climate for the benefit of society.

NASA's Earth Science Enterprise designated observable program for the 2017-2027 decade



As an orange cloud formed as a result of a dust storm over the Sahara and caught up by air currents – reached the Philippines and settled there with rain, I understood that we are all sailing in the same boat.

Vladimir Kavalyonok, USSR cosmonaut

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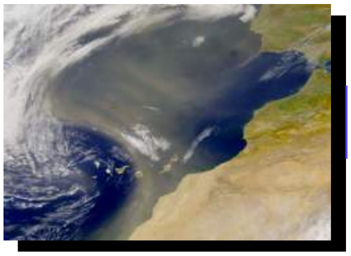


1. Executive Summary

The observation of the cosmonaut highlighted above expresses why advanced understanding of the processes that move, transform and cycle particle suspensions throughout the atmosphere are such an integral part of understanding the Earth system. These processes exert a controlling influence on our weather, climate, environment and human health. In the report of the 2017-2027 decadal survey (DS) of Earth Science and Applications from Space by the National Academies of Sciences, Engineering, and Medicine, questions central to understanding these processes were called out as a top priority to address in the coming decade. This Earth science DS was the second of its type and it converged to a final, small set of science and applications priorities and observing system priorities starting from a large number of community-provided inputs. Emerging from these were a set of five designated observables (DO's) declared to be of highest priority for the decade. Observations of aerosol (A) and separately clouds, convection and precipitation (CCP) were recommended as two of these designated observables. Since the science of each are strongly intertwined, NASA proposed these two DOs be combined into a single (ACCP) DO study. That study has defined what has become the Atmospheric Observing System (AtmOS) integrated program. Herein, we use ACCP since the report describes the DO architecture study.

ACCP seeks to quantify the consequences of the above-mentioned particle-transforming processes across time scales, ranging from seconds to minutes on sub-km scales, hours to days on meso- to near synoptic scales, and sub-seasonal to seasonal and beyond on a global scale (Fig. 1.1). ACCP will provide answers to basic questions and related applications about weather, air quality, climate and our environment that were specifically called out in the DS report. Three "most-important" DS questions serve as the underpinning science questions and are the basis of the 8 specific science objectives of ACCP. The three questions are:

(i) Why do convective storms, heavy precipitation, and clouds occur exactly when and where they do?

(ii) What processes determine the spatio-temporal structure of important air pollutants and their concomitant adverse impacts on human health, agriculture, and ecosystems?

(iii) How can we reduce the uncertainty in the amount of future warming of the Earth as a function of fossil fuel emissions, improve our ability to predict local and regional climate response to natural and anthropogenic forcings, and reduce the uncertainty in global climate sensitivity that drives uncertainty in future economic impacts and mitigation/adaptation strategies?

ACCP focuses on processes and proposes the first-ever space-based global measurements of vertical air motion occurring in convective clouds combined with the first direct measurement of aerosol extinction and other cloud and aerosol characteristics that will be vertically profiled in the surrounding environment. Understanding how air rises and sinks in clouds will improve our knowledge of processes that create clouds, severe storms, rain, snow and how water and aerosols cycle through the atmosphere. ACCP will advance knowledge of aerosols, the degree to which they interact with and are impacted by clouds and precipitation, and their contributions to air-quality events that adversely impact human health, agriculture, and ecosystems. Finally, the combined global cloud and aerosol measurements of ACCP will provide critical information linking clouds and aerosols to radiation in the Earth's atmosphere, a key to understanding Earth system feedbacks, Earth's climate and climate change, and the linkages between the energy and water cycles of the Earth system.

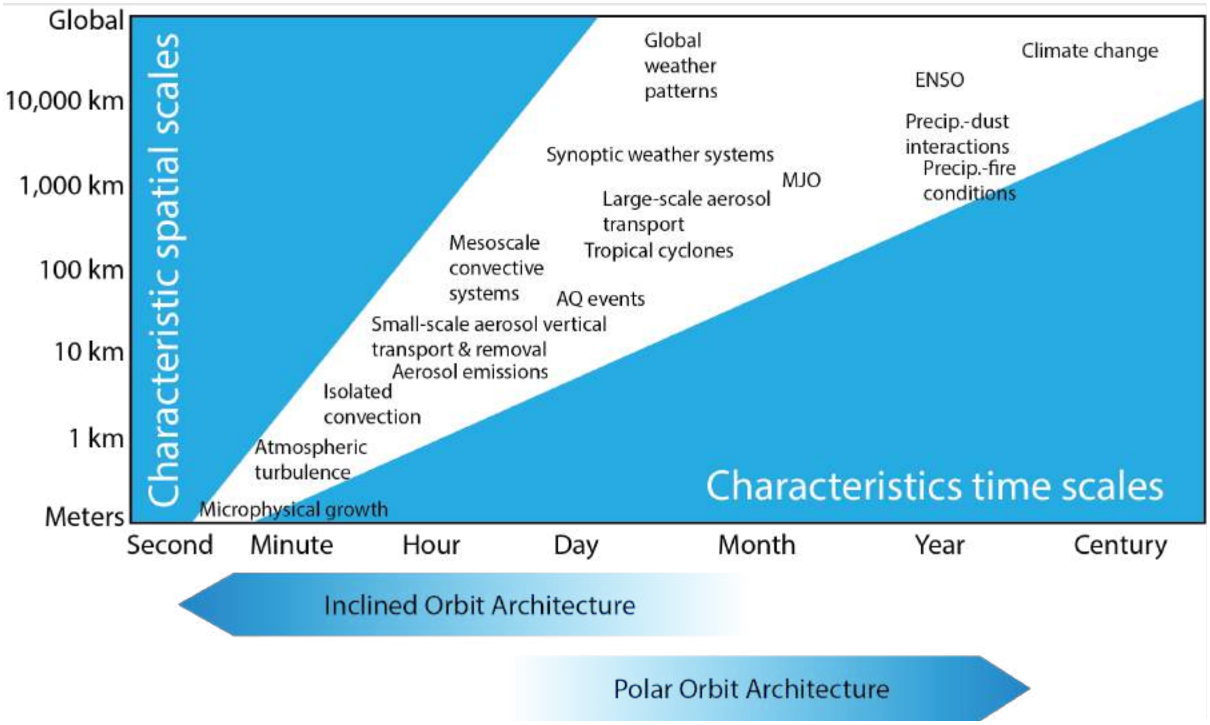


Figure 1.1 Earth system processes across time and space scales with emphasis on ACCP processes. The architecture strategy of ACCP seeks to observe consequences of processes across multiple time scales.

ACCP is a program composed of the following integrated and connected activities:

1. *Developing and implementing new global observing architectures.* New measurement capabilities for remote sensing of aerosol, cloud and precipitation microphysics and the dynamics of convective clouds and low clouds will be developed and implemented. Mission concepts that have emerged include the following two important characteristics:

   (i) Polar orbiting architectures with a single launch that maximize science capabilities for studying processes that shape our changing climate. The measurements will be made in a single polar orbital plane and will include multi-frequency Doppler radar and HSRL lidar along with complimentary passive sensors, that include microwave radiometer, polarimetry and visible/shortwave infrared (IR) and IR spectrometry.

   (ii) A dual satellite architecture in an inclined orbit that focuses on fast processes aimed at maximizing diurnal sampling of processes associated with convection and aerosol emissions.

2. *Leveraging existing Program of Record (PoR) observations.* ACCP promotes wider use of available satellite data notably, but not exclusively, exploiting the new capabilities of geostationary spectral imagery that provides a unique and complementary time-evolving context for the proposed ACCP observations. It also draws from the heritage of programs like GPM and the A-Train while extending programs that are soon to occur such as EarthCARE.

3. *Exploiting sub-orbital capabilities.* ACCP includes an active sub-orbital activity that will provide highly detailed and complementary observations of microphysical and dynamical properties that are not readily achievable from space.

4. *Advancing models, analysis and prediction systems.* ACCP will be strongly leveraged in the development of physical parameterizations in new models and for making improvements to existing models and analysis systems that are planned over the decade (Box DE).

5. *Advancing applications for decision-support.* ACCP observations will be used to address real-world challenges for societal benefit. The ACCP study applications team defined key applications criteria, identified and assessed the readiness levels of those applications, and engaged users and solicited feedback to integrate user needs in the assessment of architecture designs. Applications were focused on five thematic areas including weather, air quality, and climate modeling and forecasting; disaster monitoring and modeling; water resources; infrastructure and development; and health and air quality.

The definition of the ACCP architecture and the subsequent evaluation of this architecture flowed down from a set of 8 ACCP science objectives that quantitatively link to the three DS questions stated above. These objectives revolve around the topics of low and high cloud climate feedbacks, convective storm systems, cold cloud and precipitation processes, aerosol attribution and air quality, aerosol processing, wet removal and vertical redistribution, and aerosol direct and indirect effects. These objectives then led to a set of minimum- and enhanced-capability geophysical variables that traced to a set of measurement capabilities and ultimately to measurement requirements.

Although almost 100 architecture combinations were explored, a core, synergistic set of instrument classes emerged. While all architectures were principally framed around cloud and precipitation radars with and without Doppler capability and lidars with and without high spectral resolution (HSRL) capability, with the overall measurement approach of ACCP involving multi-sensor integration. Information derived from passive measurement systems were deemed to provide both important complements to these active systems while also significantly enhancing the capabilities of them when combined. These included information from passive microwave radiometers, multi-angle polarimeters, and spectrometers covering the ultraviolet to far IR spectral range. Architecture considerations included elements designed to measure processes at very short time scales (~30 seconds to 2 minutes) by including 2-3 identical sensors (radar, passive microwave radiometers, and stereo cameras) flying in formation to measure time rates of change of clouds, precipitation, and aerosols. Architectures included large single-satellite observing systems, constellations of a few medium-sized satellites, and larger constellations of small satellites in polar and/or inclined orbits. In addition to the orbital portion of the observing system, the study investigated science that should be addressed through a suborbital element involving both aircraft-based and ground-based observations. The suborbital elements continue to be investigated and developed and so are not discussed in detail here.

Consensus on the final three architectures proposed for ACCP was reached via a process developed under a Value Framework analysis that analyzed the science and applications benefits of the architectures, along with risk, cost and programmatic considerations. The final architecture recommendation is graphically portrayed in Figure 1.2. The inclined orbit satellites will provide crucial information on diurnally varying processes associated with deep convection and aerosol emissions and transport. A pair of radars will provide vertical profiling of clouds and precipitation while Doppler capability will enable measurement of the vertical air motions in convective clouds. A sub-millimeter passive microwave radiometer will provide for constraints on cloud ice properties, precipitation, and horizontal context. A backscatter lidar will profile aerosol and cloud properties and can be combined with a multi-angle, multi-frequency polarimeter for enhanced aerosol and cloud properties. Finally, tandem stereo cameras will provide the first-ever measurements of low cloud and aerosol plume and dynamics.

Figure 1.2. Summary of the final recommendation from the ACCP study indicating a single satellite in polar orbit and two satellites in an inclined orbit.

The polar component of the architecture, required to meet the constellation threshold objectives and to be launched one or two years after the inclined satellites, is focused on interacting cloud-aerosol-radiation processes that contribute to uncertainty in our changing climate. It features a pair of Doppler radars for vertical profiling of clouds and light-to-moderate precipitation and in-cloud vertical air motions with a focus on measuring these properties to very near the surface, a limitation of previous space-based radars. It will also include an advanced high-spectral resolution lidar for profiling of aerosol properties (type, microphysics, optical) and cloud properties. To complement these active sensors, the satellite will fly a similar sub-millimeter passive microwave radiometer and polarimeter as in the inclined orbit. Finally, to provide information on how clouds and aerosol interact with solar and terrestrial radiation, a pair of spectrometers spanning wavelengths from ultraviolet to visible to far IR will be included.

2. Introduction

The atmosphere of Earth both sustains life on the planet while shielding this life from the sun's damaging radiation. The atmosphere also transports materials around the globe in a matter of weeks, shifts heat and moisture from low latitudes to polar regions, establishing Earth's climate zones, and maintains the seasons as we know them. The atmosphere also acts as a reservoir for long-lived chemicals that remain aloft for decades potentially affecting the environment over these longer time scales. These transports, largely influenced by atmospheric convection that lofts heat, mass and trace constituents into the upper atmosphere, remains rudimentarily understood today and generally poorly represented in global Earth system models.

Although the atmosphere is composed of 99.9% oxygen, nitrogen and argon, the remaining <0.1% contains trace gases instrumental in supporting our climate and all life forms on Earth. Carbon dioxide and methane, for example, are greenhouse gases whose changing abundances over time are instrumental in perturbing Earth's climate. Water vapor, also a trace gas and the principal greenhouse gas, exerts a fundamental control on the observed temperature distribution of the atmosphere and is an essential ingredient of the Earth's hydrological cycle. The atmosphere also sustains suspensions of small particles whose sizes range from a fraction of a micrometer to millimeters (Fig. 2.1). We group these suspended particles into two general categories: aerosol particles of varying composition and size, either of solid or liquid form, and hydrometeors composed primarily of water that form clouds and precipitation. The different ways these particles interact profoundly affect both weather and climate.

ACCP will provide answers to basic questions and related applications that address how these particle suspensions influence our weather, climate and environment. In so doing, ACCP directly addresses a number of the highest priority Earth science objectives identified in the 2017 DS report (next section). A central tenet of ACCP is the recognition of the dynamical nature of the Earth system, bringing a unique focus on the microphysical and dynamical linkages between aerosols, clouds and the hydrological and energy cycles.

To address these priorities, ACCP adopts a systems approach to measurements and analysis (Box ES). It introduces a new observing system predicated on measuring processes across time and space scales that are to be integrated with other elements including the existing PoR and suborbital activities that will further probe processes unresolvable from space, all being linked to modelling and global analysis. ACCP specifically builds on the heritage of existing programs like GPM and the

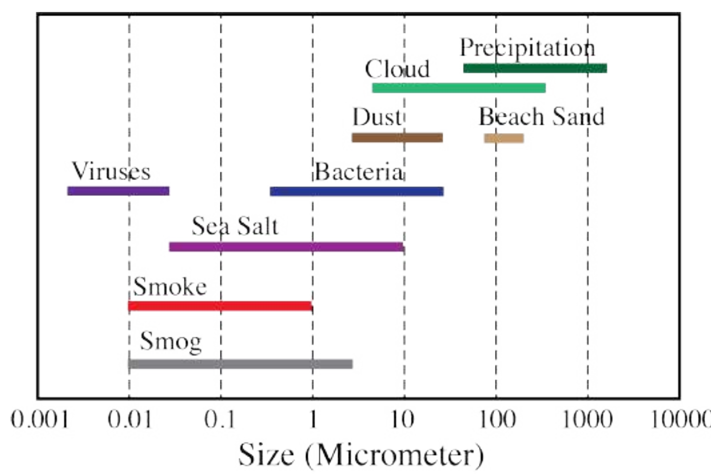


Figure 2.1 The characteristic size ranges of atmospheric particles. ACCP observations will be sensitive across these ranges and will provide some ability to discriminate between them and explore the interaction between them.

A-Train while also extending programs that are soon to occur like EarthCARE. ACCP brings specific new observing capabilities to process investigation including: (i) Doppler measurements of in-cloud air motions central to many cloud and convection processes and to prediction of severe weather (section 4.3) and (ii) direct measures of aerosol extinction from high spectral resolution lidar that constrain elusive estimates of aerosol absorption and aerosol effects on radiation as described below in section 4.7.

The ACCP measurements will advance science in several important ways that offer the opportunity for genuine discovery by implementing a measurement strategy that will deliver a number of firsts:

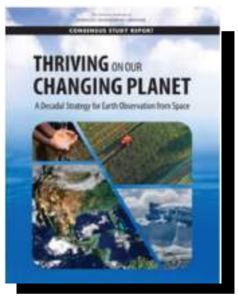
(i) *Global observations of vertical motions* — the vertical motions of clouds fundamentally shape processes that determine many of the most important properties of clouds and storms. It is a basic element of how cloud drops initially form on aerosol that then influence important properties of clouds and precipitation (section 4.3). It is fundamental to the properties of intense convection and storm characteristics (Box R) and to advancing weather prediction across multiple time scales.

(ii) *Global profiles of aerosol properties* — Vertical profiles of aerosol properties, including aerosol type and absorption, are essential for quantifying the effects of aerosol on both the atmosphere and on the radiative forcing of the climate system. A fundamental and necessary property to advance these topics, as called out in the DS, is the profile of extinction. ACCP will provide for the first time an unambiguous measure of the vertical profile of aerosol extinction that will then constrain estimates of the vertical profiles of absorption. Furthermore, the near simultaneous collocated measurements of aerosol profiles and precipitation processes will advance our understanding of aerosol removal and redistribution processes.

(iii) *Collocated dynamics, cloud microphysics and aerosol characteristics* — Aerosols, cloud and precipitation hydrometeors, vertical motion and radiation are integrally linked in ways that determine cloud feedbacks, aerosol influences on clouds and on how water is cycled through the atmosphere more generally. Global measurements of aerosols, cloud hydrometeors, vertical motion and radiation that are collocated and near simultaneous for the first time will significantly enhance our understanding and prediction of cloud and precipitation processes and aerosol interactions that link to these processes.

(iv) *Evolution of cloud and aerosol processes* — The influence of vertical motions on the properties of shallow clouds, as well as related aerosol interactions, occur rapidly over short timescales. ACCP is exploring novel ways of capturing these rapidly evolving processes by exploiting clustered formation that exploit the time difference (Δt) between measurements as an important added dimension to address these rapid processes (section 7.6).

(v) *Diurnal cycle of clouds, precipitation, aerosols and connecting processes* — The diurnal cycle is one of the most obvious and pronounced modes of forced, periodic variability of the Earth system. It occurs on a time scale closely associated with the convective process and thus has a profound influence on convection. The phasing of the diurnal forcing on convection and the processes that affect convection is however complex and not well understood, principally because we have no diurnally resolved measures of critical processes, like those determined by vertical motion. The inclined orbit of ACCP, with near simultaneous collocated observations of the vertical motions, cloud and aerosols, will reveal for the first time convective processes under different phases of the diurnal forcing and thus shed light on one of the most fundamental modes of variability of the climate system.



3. The 2017-2027 Earth Science and Applications from Space decadal survey

During the period between 2015-2017, the National Academies of Sciences, Engineering, and Medicine conducted the DS study of Earth Science and Applications from Space. This study drew from inputs from a wide sector of Earth science represented by five panels, the space sector, and applications communities. This was the second such Earth science survey and it converged to a final, small set of science and applications priorities and related observing system priorities that started from a large number of community-provided inputs. Emerging from these were a set of 15 high priority objectives that map to a set of eight DOs. These DOs were thus declared to be the highest priority observables for the decade. NASA has since commenced with a set of studies to develop these observable recommendations into a set of concrete measurements and related spaceborne architectures.

Observations of aerosol (A) and separately of clouds, convection and precipitation (CCP) were recommended as two designated observables. These two DOs, when combined, map onto eight of the most important priorities (Table 3.1). Cloud feedback was a preeminent issue considered by the climate panel, while convection and precipitation measurements were deemed vital for advancing understanding and prediction of moist convection and its influence on weather and extremes by the weather, climate and hydrology panels. Observations of aerosol were declared a high priority by the climate panel due to their influence on climate forcings as well as to air quality, which was considered to be a pressing environmental risk by the weather panel.

Through a NASA recommendation, and in recognition of the overlapping science, the two designated observables, A and CCP, were subsequently combined into a single study (hereafter ACCP). The DS recommended both A and CCP be largely focused on processes and specifically developed around spaceborne lidar and multi-angle polarimeter for A and Doppler radar and mutli-frequency passive microwave observations for CCP.

Table 3.1 The most important Science and Applications Priorities for the Decade 2017-2027 to which ACCP contribute. The three questions noted in red are considered to be the three principal science questions of ACCP. The most direct contributions of ACCP are noted in bold.

Science & Applications Area	Science and Applications Questions Addressed by MOST IMPORTANT Objectives	ACCP's contribution
Coupling of the Water and Energy Cycles	**(H-1)** How is the water cycle changing? Are changes in evapotranspiration and precipitation accelerating, with greater rates of evapotranspiration and thereby precipitation, and how are these changes expressed in the space-time distribution of rainfall, snowfall, evapotranspiration, and the frequency and magnitude of extremes such as droughts and floods?	ACCP will provide measurements of rain and snowfall and <u>indirectly</u> contribute to this objective. More importantly, ACCP will advance understanding and representation of precipitation process in models and analyses, an essential step in addressing this question: ACCP goals 1, 2 & 3, objectives O1, O3, O4.

	(H-2) How do anthropogenic changes in climate, land use, water use, and water storage interact and modify the water and energy cycles locally, regionally and globally and what are the short- and long-term consequences?	By addressing the factors most relevant to quantification of climate change (C-2 below), together with (H-1), ACCP indirectly advances this objective
Improving Weather & Air Quality Forecasts	**(W-1)** What planetary boundary layer (PBL) processes are integral to the air-surface (land, ocean and sea ice) exchanges of energy, momentum and mass, and how do these impact weather forecasts and air quality simulations?	Boundary layer clouds, and PBL properties, are central to the cloud and aerosol indirect objectives of ACCP goals 1 & 5 and objectives O1 & O8
	(W-2) How can environmental predictions of weather and air quality be extended to forecast Earth System conditions at lead times of 1 week to 2 months?	Processes that couple convection to basic internal modes of variability are the basis of S2S predication, and ACCP goal 2 and objective 3 directly contribute to this DS objective
	(W-4) Why do convective storms, heavy precipitation, and clouds occur exactly when and where they do?	**ACCP is being designed to address this question directly through ACCP goal 2, objectives O3**
	(W-5) What processes determine the spatio-temporal structure of important air pollutants and their concomitant adverse impact on human health, agriculture, and ecosystems?	**ACCP is being designed to address this question directly through ACCP goal 4, objectives O5 & O6**
Reducing Climate Uncertainty and Informing Societal Response	**(C-2)** How can we reduce the uncertainty in the amount of future warming of the Earth as a function of fossil fuel emissions, improve our ability to predict local and regional climate response to natural and anthropogenic forcings, and reduce the uncertainty in global climate sensitivity that drives uncertainty in future economic impacts and mitigation/adaptation strategies?	**ACCP is being designed to address this question directly. ACCP will make measurements that are central to the topics of aerosol forcing, critical cloud feedbacks and to aerosol-cloud-precipitation interactions. ACCP goals 1, 2, 3 & 5; objectives O1, O2, O3, O4, O7, O8.**
Sea Level Rise	**(C-1)** How much will sea level rise, globally and regionally, over the next decade and beyond, and what will be the role of ice sheets and ocean heat storage?	The properties of clouds and precipitation in polar regions has a basic influence on polar ice mass change. ACCP offers an indirect, but non-trivial contribution through goal 3, objective O4

4. ACCP science goals and objectives

Influences of suspended particles on climate and on life on Earth are governed, in part, by processes that take place on the microscopic level. These microphysical processes are in turn shaped by processes that operate on a much larger scale more typically represented by atmospheric weather patterns. The challenge to make advances on the important science topics related to these microphysical processes is to devise ways of observing these processes placing them on scales representative of both the intricate microscopic processes that determine particle properties and the larger scales typical of the weather patterns that control and organize them. The basic goal of ACCP is to develop approaches that connect processes across such time and space scales addressing the recognized most important influences of these particle-related processes on the Earth system. These important influences and the way they align with the goals of ACCP include:

Cloud feedbacks — Clouds are a dominant influence on the energy balance of Earth. The eventual response of Earth's climate system to imposed aerosol and greenhouse gas forcings depends on how clouds change in response to these forcings. These responses, referred to as cloud feedback, are the recognized principal source of uncertainty in climate model projections of global warming. Making progress on quantifying the feedbacks especially associated with low and high cloud responses were deemed as one of the highest priorities for the coming decade and it is widely acknowledged that addressing this priority requires making some advance in jointly quantifying cloud and precipitation processes. ACCP has a specific focus on high and low cloud related feedbacks and adopts a process orientated approach to address them. The approach is to link measurements of process-centric variables both to the environmental state in which they form and to other cloud properties such as their cloud physical and radiative properties. This approach leads to the first ACCP goal listed below.

ACCP Goal 1*: Cloud Feedbacks: Reduce the uncertainty in low- and high-cloud climate feedbacks by advancing our ability to predict the properties of low and high clouds.*

Atmospheric convection — Life on Earth is tightly bound to convective weather systems from the life-giving fresh water they supply to the life-threatening extreme weather they produce. Deep convective storms are found throughout the tropics and mid-latitudes, are often associated with large-scale weather regimes, and vary in structure from isolated thunderstorms to highly organized storm complexes. These storms are driven by processes that transform hydrometeors producing sources of energy that drive weather systems and storms that are also the sole source of precipitation in many regions of our planet and are recognized as playing a vital role in the Earth's weather and climate system. The more ubiquitous shallow convection, too, is an essential part of the way water is cycled throughout the Earth system and also an essential stage of the deep convective lifecycle. The formation of precipitation from convection, when organized into large weather systems, produces latent heating that not only fuels these systems but is a fundamental source of energy that drives the larger scale atmospheric circulation, moving heat poleward and defining our planetary climate regimes. Advances in prediction of weather events, precipitation, and climate change and its influence on our water supply require major advances in observing convection, leading to the second ACCP goal.

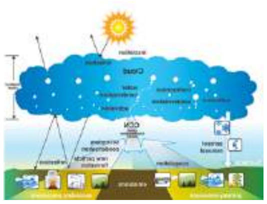
ACCP Goal 2*: Storm Dynamics: Improve our physical understanding and model representations of cloud, precipitation and dynamical processes within convective storms.*

Cold cloud processes and the water and energy balances of cold climate regimes — The cold and dry climate regimes of the planet are acutely sensitive to the external forcings that are currently being imposed on our climate system. The processes that produce snowfall and the cloudiness from which it falls fundamentally influence the Earth system and these cold dry regions in particular. This is exemplified through the influence on the surface mass and energy balances on the polar ice sheet mass change, on sea ice and on the disproportionate effect of mid- and high-latitude mixed-phased clouds on climate sensitivity. Thus, goal 3 focuses on these important cold clouds.

ACCP Goal 3: Cold Cloud and Precipitation: Improve understanding of cold (supercooled liquid, ice, and mixed phase) cloud processes and associated precipitation and their coupling to the surface at mid to high latitudes and to the cryosphere.

Aerosol effects on human health and the environment — Aerosol are also key contributors to local and regional air pollution and are thus linked to human health impairment, life expectancy, the health of terrestrial and marine ecosystems, affecting transportation systems and the generation of solar power among other societal impacts. Outdoor air pollution is estimated to cause over 4 million premature deaths annually around the world with most being attributed to particulate matter < 2.5 µm in diameter ($PM_{2.5}$) and to species with high oxidative potential. Most of these small particles are formed in the atmosphere via aqueous phase gas-to-particle conversions that take place within clouds. The clouds also play a key role in the removal of the particles by wet deposition processes. Measurements of both clouds, aerosols and their specific source attribution will improve the parameterization of these processes in earth system models. These improvements will enhance air quality forecasts, directly impacting public health outcomes for vulnerable populations and many other applications of direct societal relevance. These factors motive the fourth ACCP goal.

ACCP Goal 4 Aerosol Processes: Reduce uncertainty in key processes that link aerosols to weather, climate and air quality related impacts.



Aerosol effects on climate — It is clear that aerosol produced as result of human activity are impacting the energy budget of the Earth System, thereby altering climate, through direct radiative forcing, and indirectly by their influence on clouds. Aerosols are also possibly affecting precipitating weather systems in a number of ways not yet fully understood. This includes the suppression of rain in shallow clouds and intensification of precipitation on other weather regimes including enhancements of lightning in convective storms (Box CI). Understanding the global extent of the response of the Earth system to aerosol remains one of the major challenges facing Earth system science in the coming decade and ACCP strives to make advances in meeting these challenges with the following goal.

ACCP Goal 5: Aerosol Impacts on Radiation: Reduce the uncertainty in Direct and Indirect aerosol-related radiative forcing of the climate system.

These five goals map directly to the DS priorities in the way highlighted in Table 3.1. To meet these goals, ACCP defines eight distinct, but connected objectives that are now described. These objectives are divided into a minimum objective and an enhanced element . In this way a minimum set of requirements could be identified for each objective augmented by an enhanced set of requirements, which furthers the science in important ways.

4.1 Objective O1: Low Clouds

Underlying science question: To what extent can the properties of low clouds be determined by environmental factors?
Minimum: Determine the sensitivity of boundary layer *bulk* cloud physical and radiative properties to large-scale and local environmental factors including thermodynamic and dynamic properties.
Enhanced: Adds to Minimum cloud *microphysical* properties and enhanced bulk cloud properties.

4.1.1 Rationale

As noted previously, the single most influential factor defining Earth's climate sensitivity are cloud feedbacks. Although the IPCC AR5 & AR6 assessments assert with some confidence the net cloud feedback to be positive, and that low clouds are one of the dominant factors in these feedbacks, there remain serious uncertainties in representing low clouds in global models. These include systemic biases as expressed by the persistent too few-too bright bias (Nam et al. 2012), and the persistent drizzle bias, (Stevens et al 2010). What has emerged both with respect to these low feedbacks and to their responses to aerosol affects addressed below in O8 is the appreciation of the importance of a wider range of cloud physical processes, connecting cloud properties to precipitation and to the cloudy sky environment.

The rationale for minimum objective derives from the recognition that the first-order problem is to quantify the water balance of low clouds by measuring cloud and precipitation properties jointly in relation to the environment in which they form. The relation between these water properties and cloud microphysical properties is also an essential aspect of the objective. While the cloud microphysical properties developed under the minimum are more bulk layer-mean properties, the enhanced objective strives to develop more vertically resolved properties, including at or near cloud top, profiles through the cloud, and advanced methods to determine cloud droplet concentration using the combination of the joint cloud and precipitation measurements.

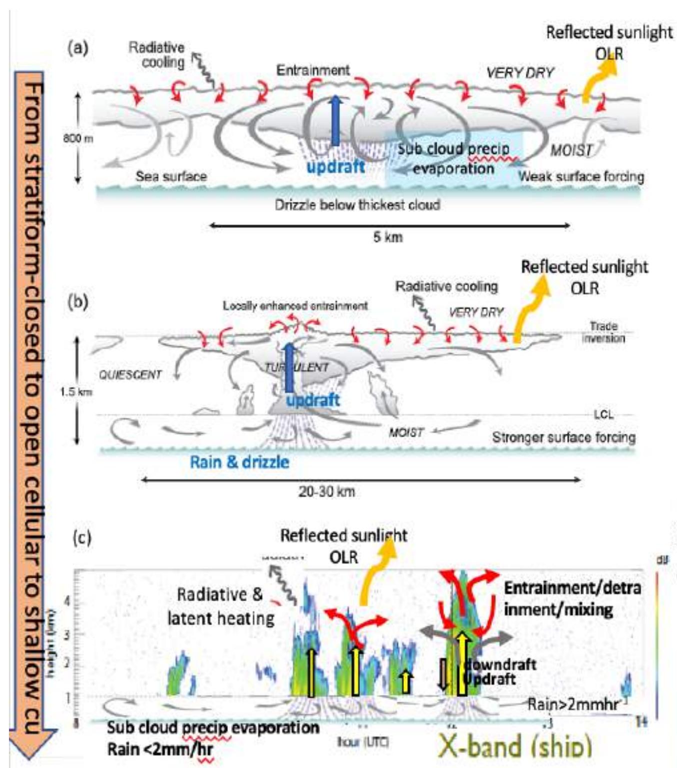


Figure 4.1. Illustration of the processes that determine the coverage and albedo of low clouds, which then determine the radiative impact of these clouds.

4.1.2 Processes and variables

The collection of processes that are central to the O1 objective is highlighted in Fig. 4.1. Objective O1 is concerned with understanding how these processes evolve with changes in the cloud environment so that we can better predict the response of low clouds to climate change and improve their representation in models. O1 is developed out of the understanding that quantification of cloud-related climate feedbacks and our ability to represent these in Earth system models ultimately rests on advancing the basic representation of clouds properties, the processes that determine them, and the influences of the environment in which they form. The properties related to the processes important to this objective are the radiative properties of the clouds, their bulk microphysical and optical properties, mesoscale structure such as cloud amount and spatial structure of precipitation, and the sub-cloud precipitation. The enhancements include cloud vertical motion, cloud top motion, advanced microphysics including profile of drop size and bulk layer droplet number concentration and additional properties of cloud top drop size distribution.

4.1.3 Key advances

The decade of ACCP also occurs at a time of significant developments in modeling (Box DE), in the program of record (Box GEO), and in potential advances in environmental monitoring and analysis. These advances position the community to better use ACCP observations. The proposed combination of measurements of ACCP will also extend existing data records developed from heritage measurements. These include augmenting the lidar and W-band radar records of CALIPSO and CloudSat which are to be extended further by EarthCARE, and the precipitation data record of TRMM and GPM. The unique value of active sensor measurements in creating these new climate data records is highlighted in Box CDR.

ACCP is also a significant advance over existing heritage measurements such as from the A-Train for addressing low cloud processes, offering measurements being potentially transformative to this topic. Table 4.1 summarizes key advances on selected variables that are expected to occur given the measurements being proposed, noting also those that will potentially have high impact in achieving the O1 objective. Advancements beyond CloudSat/CALIPSO would include resolved profiles of precipitation within the PBL, better discrimination of cloud and precipitation within PBL clouds, including better ways to determine cloud base precipitation, and capabilities that will improve our understanding of the transition between processes. ACCP will also deliver cloud microphysical properties that are a substantial advance on capabilities today. These including size distribution information at cloud top, cloud particle size profile information through the cloud and significant improvements on cloud drop number concentration information. The dynamical context provided by ACCP measurements is also transformative. The motion information projected from a W-band Doppler radar is a major step forward for studying low-cloud processes and shallow convection processes (Fig. 4.1). The cloud top motion potential from time differenced measurements offers unique opportunities to address cloud top processes including that of entrainment.

Table 4.1. Key ACCP geophysical variables and science advances for O1. Acronyms include SW, shortwave; LW, longwave; VIS, visible; NIR, near infrared; CRE, cloud radiative effects; TOA, top of the atmosphere; sfc, surface; No, number concentration; PoR, Program of Record.

Variable (minimum)	Variable (enhanced)	Measurement advances of A-Train	Transformative
	Vertical air motion (>1 ms^{-1})	W Doppler radar (W band), >0.5m/s	Vertical motion at 0.5 m/s
Cloud top height & particle number concentration (No)	Cloud top variance	Lidar & polarimeter	
Liquid water path		Shortwave (SW) spectral visible (VIS) & near infrared (NIR), radar brightness temperature	
Precipitation profile (sub cloud)	Profile to 500m or below	Radar Δz~240m providing sub-cloud precipitation	Higher resolution profile to surface
'Mesoscale' structure (< 1km)		SW VIS spectral imagery, sub km, stereo camera	Stereo camera measure of cloud-top mixing across scales
Environmental and diurnal properties		ACCP inclined orbit and PoR (e.g., geo. satellite), analyses	Diurnally resolved cloud properties
Cloud optical properties — bulk & profile		SW VIS & NIR spectral	Number concentration and profile of effective radius
Longwave (LW) & SW cloud radiative effects (CRE) (TOA)	LW&SW CRE (sfc)	SW VIS & NIR spectral, LW spectral	Spectral radiation budget @ cloud scale Radiation kernels

4.2 Objective O2: High Clouds

Underlying science question: How do the properties and formation of high clouds relate to (i) deep convection and (ii) large-scale environmental factors?
Minimum: (1) Relate the vertical structure, horizontal extent, ice water path, and radiative properties of convectively generated high clouds to convective vertical transport. (2) Relate the vertical structure, horizontal extent, ice water path, and radiative properties of *large-scale* high clouds to environmental factors.
Enhanced: Adds to Minimum cloud *microphysical* properties and enhanced bulk cloud properties.

4.2.1 Rationale

High clouds are often defined as those occurring at pressures below about 400 hPa [e.g., 440 hPa in IPCC AR5 (2013)], which translates to altitudes above about 7km, with this level typically higher (lower) in tropical (polar) regions. Temperatures at these levels are well below freezing and thus most high cloud particles and hydrometeors are solid/frozen. High clouds are often categorized into "convectively-generated" (red ovals in Fig. 4.2) or "synoptic" high clouds (yellow ovals in Fig. 4.2), with the former associated with deep convection and severe storms and latter labeling owing to their generation from slow, *large-scale* atmospheric vertical motion and circulation features.

High clouds contribute to cloud-climate feedback through potential changes in response to climate warming in a number of factors, including their frequency and horizontal cover, cloud-top height, and their radiative opacity, which is primarily modulated by their thickness and cloud particle amounts and types (e.g., see gray items in Fig. 4.3). These cloud features can vary and combine in ways to produce a substantive range of radiative impacts on the atmosphere and surface. For example, the albedo of high clouds can range from nearly one (i.e., almost complete reflection of the incoming solar) for deep convective clouds, and the thickest of anvil clouds they generate, to nearly zero (i.e., nearly transparent to solar radiation) for the thinnest of cirrus clouds. While this substantive range of impact on the solar radiation is similar to the case for low clouds, it's their huge impact on the infrared radiation that sets them, and their potential climate feedbacks, apart from low clouds. Specifically, because their cloud tops are so high, and thus cold, opaque high clouds are very effective at muting the infrared emission from the warm lower atmosphere/surface that cools the planet, trapping that heat in the atmosphere, and resulting in a severely reduced infrared cooling of the surface in regions of high clouds.

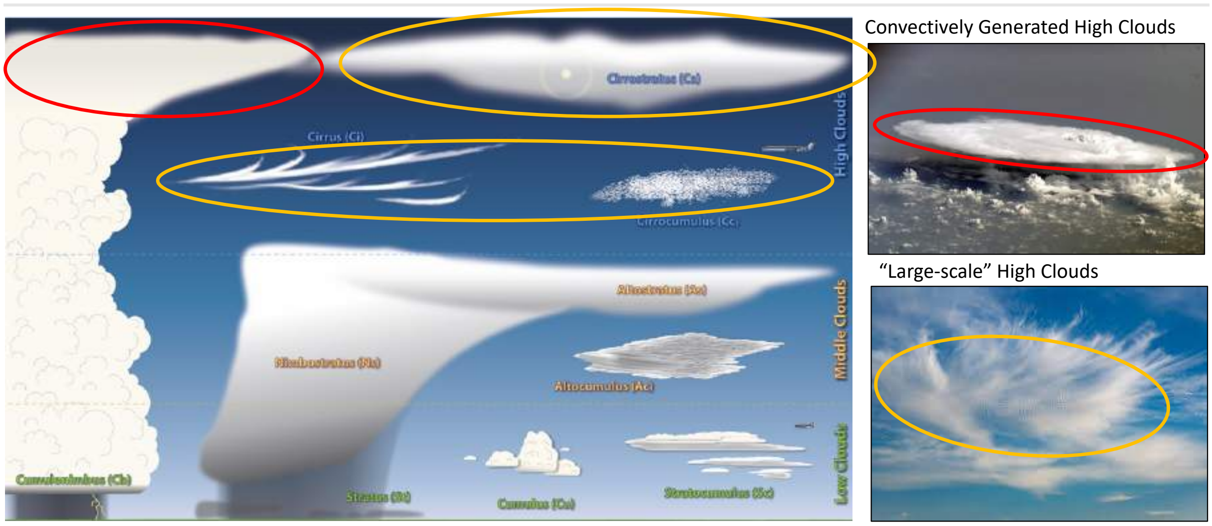


Figure 4.2. (left) Schematic illustration of cloud types, with convectively generated high clouds highlighted by the red oval, and so-called "large-scale" high clouds highlighted by the yellow ovals (source: www.weather.gov). (right) Photograph of convectively generated high cloud, specifically a thick cirrus anvil cloud generated from a deep convective system (upper) and of a large-scale cirrostratus cloud (lower).

These substantial effects on the solar and infrared radiation from high clouds can result in a range of net radiative impacts. For convectively generated high clouds, the cooling by solar reflection and heating by infrared trapping can nearly compensate, with the potential imbalance depending on macro- and microphysical features of high clouds in ways that are still uncertain. For large-scale, thin high clouds (e.g., cirrus), the absence of strong solar reflection results in a radiative warming, with the magnitude of warming also depending on their macro- and microphysical details. Knowing how prevalent each of these high cloud types are, how their macro- and microphysical properties depend on the local environment, and how these properties influence solar and infrared radiation (e.g., the gray and red parts of Fig. 4.3), is essential to understanding how high clouds are responding to climate change. For example, if warming from climate change results in thicker high clouds, the thickening will act to reduce the warming; if climate change results in higher/colder cloud tops or more frequent large-scale thin high clouds, these changes will act to exacerbate the warming. The response of tropical anvil cloud area to climate warming represents one of the largest cloud feedback uncertainties. Modeling of these clouds is highly sensitive to the microphysics within convective updrafts. Estimates of tropical anvil cloud amount feedback from observations and from models are inconsistent. Collocated observations of vertical motion and microphysics are needed to resolve current inconsistencies.

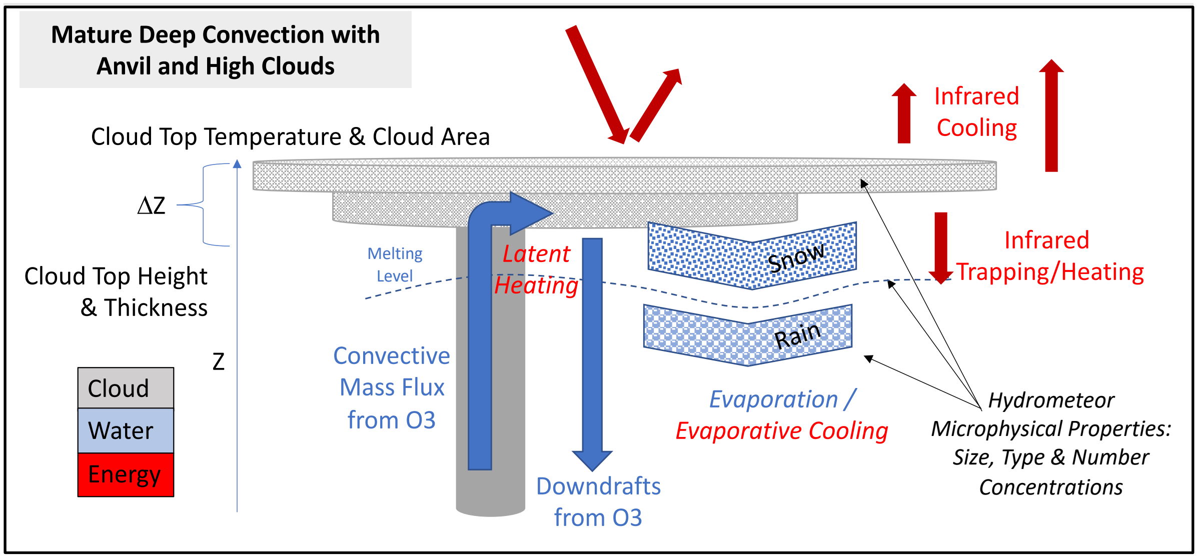


Figure 4.3. Schematic illustration of a convectively generated high cloud (gray), and its influences on, and interactions, with the water (blue) and energy (red) processes. These include the following dependencies important to understanding high cloud–climate feedback [for simplicity, the thermodynamic structure (i.e. water vapor and temperature) is not shown]: 1) solar (reflective) cooling dependence on cloud area & thickness, and hydrometeor micro-physical properties, 2) infrared above-cloud cooling and below-cloud heating dependence on cloud top height, area and thickness, and hydrometeor micro-physical properties (and thermodynamic structure), 3) cloud area, cloud top height, cloud thickness, and hydrometeor micro-physical properties dependence on convective mass flux (and thermodynamic structure), 4) vertical structure of precipitation (intensity, type) and evaporative (intensity) dependence on cloud macro- & micro-physical properties (and thermodynamic structure), 5) thermodynamic structure (not shown) dependence on shortwave and longwave radiation.

While there have been significant gains in our understanding of high cloud – climate feedbacks, there are still uncertainties in the anticipated response of high clouds to a warming climate (e.g., see Fig. 7.10, 7.11 in IPCC 2013), including potential: 1) increases in cloud opacity related to increased water content and more (less) liquid (ice) that will increase solar reflection and cooling but also infrared trapping and warming, 2) increases in cloud top height that will increase infrared trapping and warming, 3) changes to the frequency, cover and opacity of cirrus clouds, and 4) changes to the planetary-scale distribution of high clouds via changes in lapse rate or large-scale circulation and storm-tracks. ACCP's Objective 2 is designed to observe the relationships between high cloud characteristics, solar and infrared radiation, and the local dynamic and thermodynamic environment, in order to improve our understanding and modeling capabilities concerning cloud-climate feedback and reduce uncertainty in future projections of climate.

4.2.2 Processes and variables

Objective O2 is concerned with the interactions between high clouds, solar and infrared radiation, precipitation processes, and the local thermodynamic and dynamic environment. For the case of convectively generated high clouds, key variables and interactions are highlighted in Fig. 4.3, with an indication of how the clouds interact with solar and infrared radiation, and how they couple to key atmospheric dynamic and hydrological processes (see caption). Most of the features and processes also hold for large-scale high clouds, but with the localized strong convective vertical motion replaced by weaker vertical motion associated with the large-scale circulation, and with no precipitation. ACCP observations will provide information on these features to: 1) determine how the radiation impacts of high clouds depend on their macro- and microphysical properties, 2) determine how these properties depend on the radiative, dynamical, and microphysical processes occurring in the cloud system, and 3) determine how these water and energy processing mechanisms depend on convective mass flux and other environmental conditions. Key geophysical variables needed to achieve O2 are summarized in Table 4.2.

4.2.3 Key advances

ACCP will provide the means to better address key questions related to high cloud climate feedback. These include determining: 1) how radiation impacts of high clouds depends on their macro-physical and micro-physical properties (i.e., how the red arrows depend on the gray quantities in Fig. 4.3), and 2) how these macro- and micro-physical high cloud properties depend on the thermodynamics and dynamics of the cloud system, with the latter including altogether new information on convective-scale vertical motion (i.e., how the gray quantities depend on the blue arrows). Key enhancements by ACCP over the past and current POR include: a) cloud vertical motion and convective mass flux, cloud top motion (blue elements in Fig. 4.3), b) advanced microphysics characterization of cloud and precipitating particle, including their vertical profiles (gray elements in Fig. 4.3), and c) collocated cloud, radiation and dynamics (i.e. vertical motion) observations, with vertical and horizontal sampling scales commensurate with length scales of the variations in high clouds (O(kms)). Taken together, the advances by ACCP will provide a means to significantly advance our knowledge of the processing of water, latent and radiative energy in high cloud systems, and reduce uncertainties associated with high cloud climate feedback.

Table 4.2 summarizes key advances on selected variables that are expected to occur given the measurements being proposed, noting also those that will potentially have high impact in achieving the O2 objective. Advancements beyond CloudSat/CALIPSO and GPM would include better resolved profiles of precipitation for light to heavy precipitating conditions, from cloud top to cloud base, and with better discrimination of cloud and precipitation and between liquid and frozen hydrometeors. ACCP will also deliver cloud microphysical properties that are a substantial advance on capabilities today. These including size distribution information, cloud and precipitation particle size profile information. The dynamical context provided by ACCP measurements is also transformative. The motion information projected from a multi-frequency Doppler radar is a major step forward for studying convectively generated high clouds. For studying cloud-climate feedback, the ability to also have collocated solar and infrared radiation measurements at the relevant scales for high clouds and that match the footprints for cloud and dynamics information is essential and also transformative.

Table 4.2. Key ACCP geophysical variables and science advances for O2. Acronyms include Tb, brightness temperature; SW, shortwave; LW, longwave; VIS, visible; NIR, near infrared; CRE, cloud radiative effects; TOA, top of the atmosphere; sfc, surface.

Variable (minimum)	Variable (enhanced)	Measurement advances over A-Train	Transformative
Vertical air motion @ single upper level	Vertical air motion (>2 ms^{-1})	Multi-frequency radar (e.g., W, Ka, Ku), with Doppler capabilities	Vertical motion in convectively generated high cloud systems
Ice water path		Multi-frequency radar dBZ and brightness temperature (Tb), sub-mm microwave radiometer	Combined active-passive retrieval on identical footprints
Ice water content profiles		Lidar, multi-frequency radar dBZ, and Tb, sub-mm microwave radiometer	Combined active-passive retrieval on identical footprints
Precipitation phase	Precipitation rate profile	Multi-frequency radar profiling (e.g., W, Ka, Ku)	Profiling of small to large hydrometeors, with light to heavy precipitation in high clouds, through entire column to cloud base
	Particle size and density	Multi-frequency radar dBZ and Tb, sub-mm microwave radiometer	Combined active-passive retrieval on identical footprints
Cloud optical properties — bulk & profile		SW VIS & NIR spectral	Coincident cloud-scale cloud and radiative properties
Longwave (LW) & SW cloud radiative effects (CRE) (TOA)	LW&SW CRE (sfc)	SW VIS & NIR spectral, LW spectral	Spectral radiation budget @ cloud scale Radiation kernels

4.3 Objective O3: Convective Storm Systems

Underlying science questions: How does convective mass flux relate to the vertical distribution and microphysical properties of clouds and precipitation in deep convection? How do different convective storm systems contribute to vertical transports of heat, water, and other constituents within the atmosphere and how do these transports relate to storm environment and life cycle?

Minimum: Relate vertical motion within convective storms to their a) cloud and precipitation structures, b) microphysical properties, c) local environment thermodynamic and kinematic factors such as temperature, humidity, and large-scale vertical motion, and d) ambient aerosol loading.

Enhanced: Improve measurements of convective storm vertical motion and storm characteristics in (a) and (b) of the Minimum objective to better address deep convection and diurnal variability. Further relate items in the Minimum objective to latent heating profiles, storm life cycle, ambient aerosol profiles, and surface properties.

4.3.1 Rationale

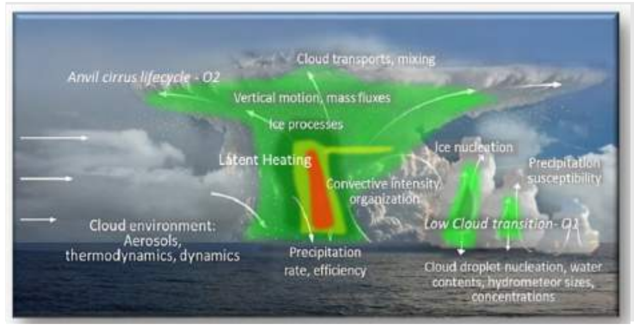


Figure 4.4. Convective storm cloud and precipitation processes occur over a range of scales and are influenced by a range of environmental factors. Broad shields of anvil cirrus often produced in detrainment of ice aloft also directly couple convective storm Objective 3 to high-cloud Objective 2.

The physical processes intrinsic to convective storm occurrence, intensity, and lifecycle are fundamental to components of global weather and climate. These processes act and occur through the full depth of the troposphere, influencing distributions of cloudiness at multiple altitudes, precipitation frequency, intensity and amount, vertical profiles of atmospheric composition, and the large-scale circulation through integrated feedbacks in diabatic heating, momentum exchanges and radiation (through detrainment processes associated with cirrus anvils). From a societal perspective convective storms are often beneficial, for example, producing freshwater via rainfall. Conversely, convective storms can result in unfavorable societal impacts associated with production of extreme weather at local to regional scales in the form of strong winds, flooding, hail, and occasional tornadoes.

Considering the integrated importance and global impacts of convective storms, it is therefore important to monitor, study, understand, and predict their behavior. The desired prediction scales range from that of a local daily weather forecast to that of integrated changes in and sensitivities to, regional and global climate. In response to this need, the 2017 Earth Science Decadal Survey identified “Why do convective storms occur where and when they do?” as a most-important (MI) weather-theme science question (W-4). It was also recognized that implicit to answering this question there is a need to better understand convective storm physical processes.

From a process perspective, questions pertaining to moist convection are generally rooted in the need for improved representation of *convective cloud processes* (e.g., Fig. 4.4) in global numerical weather and climate prediction models. This is especially true given the expected improvements in spatial and temporal resolution of models, which in turn drive new requirements on the realistic representation of cloud-scale physics at increasingly finer model grid scales. Key convective processes and resultant impacts of interest are strongly manifested in the convective cloud vertical column, driven largely by the intensity and profile of moist convective up and down drafts. These convective vertical motions are in turn controlled by variable local and regional thermodynamic, aerosol, and kinematic environments, within which convective clouds form, evolve, and grow in vertical and horizontal scale. Accordingly, the Decadal Survey MI W-4 science priority included the objective to “Measure *the vertical motion within deep convection to within 1 m/s and heavy precipitation rates to within 1 mm hour^{-1} to improve model representation of extreme precipitation and to determine convective transport and redistribution of mass, moisture, momentum, and chemical species.*” Addressing this objective also directly or indirectly maps to and impacts multiple other science questions and objectives posed in the Decadal Survey under the Climate, Weather, and Hydrology science priority themes.

In response to Decadal priorities, the ACCP observing system was explicitly designed to measure and quantify coupled convective vertical motion, precipitation, and resultant process profiles over a wide variety of global spatial and temporal environments; in turn, reflecting the continued need to understand the fundamental process "building blocks" of convective storms. Importantly, the "building blocks" are strongly coupled and include: 1) environmental forcing and recognized prominent influences of the diurnal cycle of solar radiation and underlying surface character on initiation, intensity and organization of connective storms and precipitation (Fig. 4.5); 2) in tandem with (1), up and downdraft intensity and vertical profile; and 3) as a result of and in concert with (1) and (2), associated profiles of storm microphysical processes and precipitation rates.

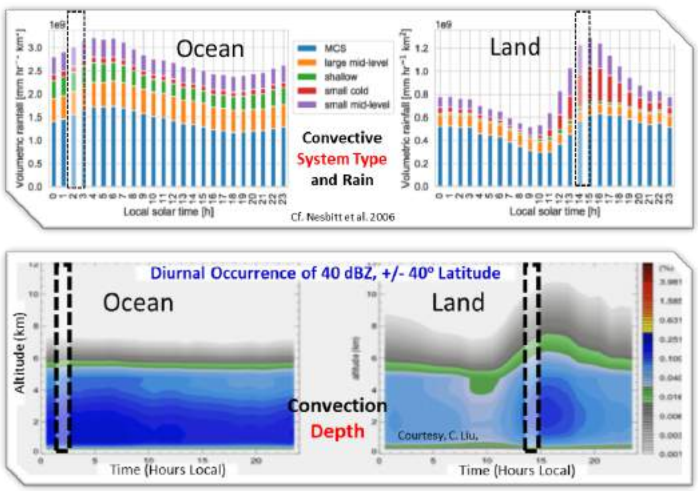


Figure 4.5. The diurnal cycles of (top; Nesbitt et al. 2006) convective rainfall and (bottom) vertical structure as represented by 40 dBZ radar reflectivity height (courtesy C. Liu, Texas A&M University-Corpus Christi), are strongly modulated to produce an afternoon and early evening peak over land, much broader, less amplified nocturnal peak over the ocean.

4.3.2 Processes and variables

Objective O3 is motivated by a need to improve understanding of coupled convective dynamics and microphysical processes as modulated by relevant forcing in the convective environment (e.g., the diurnal cycle over land and ocean; Fig. 4.5) while also serving as a statistically robust tool for observationally verifying representation of convection in cloud model physics. Representation of convection in prediction and diagnostic models depends on the scale and intent of the model used. For example, cloud resolving models, almost certain to be a standard for use in weather prediction in the ACCP era, require improved observational and physical constraints on the evolution of ice phase processes and resultant precipitation profiles as coupled to storm dynamic intensity and growth, and vice versa (e.g., Varble et al. 2014). Here ACCP geophysical variables (GVs; Table 4.3) focus strongly on coincident measurements of the profile of vertical air motion together with cloud depth (cloud top height) and related cloud component types (convective and adjacent stratiform cloud) and geometry, profiles of precipitation rate and type, and ice-water path (total water path as a baseline target). Note that in product form, the vertical motion combined with PoR or model analysis profiles of water vapor and ACCP-observed hydrometeor content essentially provide an instantaneous measurement that at least partially constrains the rate at which processes occur in the convective cloud column. Moreover, the vertical profile of combined updraft and hydrometeor contents also provide constraints on convective anvil detrainment processes important to O2.

Table 4.3. Key ACCP geophysical variables and science advances for O3. Acronyms include MF, multi-frequency; Tb, brightness temperature; HSRL, high-spectral resolution lidar; PBL, planetary boundary layer; PoR, Program of Record.

Variable (minimum)	Variable (enhanced)	Measurement advances over A-Train	Transformative
In-cloud vertical air velocity $\|>2\ ms^{-1}\|$, at/above melting layer	$\|>2\ ms^{-1}\|$, through full column	Multi-frequency (MF) (e.g. Ku/Ka/W) Doppler radar profiling	Vertical motion in convective storms at convective scale footprints
Ice water path		MF (Ku/Ka/W) Doppler radar profile and brightness temperature (Tb) w/sub-mm microwave radiometer	Combined MF active-passive retrieval with hydrometeor Doppler velocity constraint on identical footprints
Hydrometeor vertical feature mask		MF (Ku/Ka/W) Doppler radar, Lidar profile	Combined active retrieval of hydrometeor column structure and cloud top
Cloud geometric top temperature		MF (Ku/Ka/W) Doppler, Lidar, and spectrometer	Combined retrieval accuracy
Precipitation rate profile		MF (e.g., Ku/Ka/W) Doppler radar profiling and Tb w/sub-mm microwave radiometer	Combined active-passive retrieval with hydrometeor Doppler velocity constraint on identical footprints
Precipitation phase		MF (e.g., Ku/Ka/W) Doppler radar profiling and Tb w/sub-mm microwave radiometer	Profiling of small to large hydrometeors and motion in light to heavy precipitation through cloud column
	Particle size and density	MF (e.g., Ku/Ka/W) Doppler radar profiling and Tb w/sub-mm microwave radiometer	Combined active-passive retrieval with hydrometeor Doppler velocity constraint on identical footprints
	Total water path	MF (Ku/Ka/W) Doppler radar and Tb w/sub-mm microwave radiometer	Combined MF active-passive retrieval on identical footprints
Aerosol fine mode optical depth (column/PBL)		HSRL Lidar, polarimeter	More accurate aerosol profile
Aerosol Optical Depth (column, PBL)		HSRL Lidar, polarimeter	More accurate aerosol profile
	Aerosol number concentration	HSRL Lidar, Polarimeter	Profile
Lightning		Addition of PoR spatial/temporal continuous Geostationary Lightning Mappers/Lighting Imager	Combined global convective vertical motion and hydrometeor profiles for individual storms over diurnal cycle

Also, of great importance is a partitioning and improved understanding of how environmental state variables in the low-level storm environment (temperature, humidity and wind) and ambient aerosol profiles collectively interact to impact storm evolution, intensity and precipitation processes (e.g., Tao et al. 2012). To this end, ACCP GVs related to O3 focus on inclusion of model-analyses of environmental state, combined with ACCP and PoR measurements of aerosol optical depth and profile characteristics to combine with the convective cloud profile measurements

Considering simulations and prediction at climate scales, General Circulation Models (GCMs) will likely evolve to resolutions permitting explicit simulation of similar processes at cloud scales, and hence the same geophysical variables and process observations apply. Alternatively, it is also likely that several GCMs will continue to use convective parameterizations relating adjustments of the moist atmosphere to convective cloud-based spectral representations of convective mass flux etc. (e.g., Arakawa Schubert 1974, Labouz et al. 2017). In this context ACCP-measured global statistics on convective updraft properties and associated mass-flux profile as a function of location and occurrence in the diurnal cycle, via the vertical motion GV and cloud top height (ACCP and PoR), will provide a direct statistical reference against which to test cloud spectral representations of convective mass flux in GCMs.

4.3.3 Key advances

ACCP will provide a highly synergistic, transformative global spatial and diurnally varying temporal ensemble of convective storm vertical profile measurements of in-cloud vertical and hydrometeor (e.g., Doppler velocity) air motion together with coincident profiles of hydrometeor content, precipitation phase and rate, column-integrated water paths, and cloud top height (cf. Table 4.3). Moreover, these observations will be collected in the context of ACCP-observed profiles of aerosol character, the broader context swath of cloud top motion and horizontal wind, and passive microwave measurements, and global model analyses of storm thermodynamic and kinematic environments. Collectively the observations provide a highly complementary dataset for robust multivariate statistical characterization of convective cloud dynamics and microphysical processes that define the vertical structure of convection. Analysis of observations supporting O3 process studies will also naturally extend to study of associated convective detrainment of ice and water substance in anvil cirrus, providing a process overlap to the ACCP O2 high-cloud objective.

The measurements will significantly enhance and extend multi-year climatologies of convective precipitation and cloud structure statistics collected in previous satellite missions (TRMM, CloudSat, GPM). It is anticipated that the suite of O3-related data products will also leverage and constrain products produced under the broader observational purview of Program of Record Geostationary (GEO) satellites (e.g., convective cloud top tendency and/or overshoot-inferred motion and intensity properties; Bedka et al. 2012; Luo et al. 2014; Mecikalski et al. 2016).

Statistical integration of the convective storm data will improve our understanding of convective process building blocks, and through improved physical constraints, positively impact the fidelity of conceptual and physical models of convection from cloud system to climate scales (e.g., O'Gorman and Schneider 2009; Varble et al. 2014; Lebo et al. 2017; Lebouz et al. 2017).

4.4 Objective O4: Cold Cloud and Precipitation Processes

Underlying science questions: What are the processes that govern phase partitioning and precipitation formation in cold clouds? What are the vertical structures of microphysics of cold-cloud precipitation from cloud top to near-surface and associated microphysical processes? How do mixed-phase properties of clouds impact their radiative properties and change the resultant radiative fluxes? What is the distribution and phase of surface precipitation (rain, mixed phase, frozen and snowfall) and how does it influence the surface water and energy balance?

Minimum: Detect and quantify vertically integrated amounts of ice and liquid condensate (including precipitation) and relate these to vertical structure, cloud physical and radiative properties (including mixed-phase precipitation and snowfall), meteorological forcing and regime, orography, and surface properties.

Enhanced: Enhancement of Minimum with an additional focus on: 1) vertical profiles of ice and liquid condensate, 2) cloud physical processes related to the density and microphysical characterization of snowfall and frozen precipitation in the column and near surface, and 2) characterization of atmospheric contributions to the surface water mass and energy balance at higher latitudes.

4.4.1 Rationale

Mixed-phase water content in clouds is important to climate feedback processes and is strongly linked to snow formation and precipitation, which is important for radiation and surface mass balance. This objective focuses on cold clouds, defined here as clouds existing in regions with surface temperatures <0°C, e.g., focused on high-latitude regions. Several studies have demonstrated the impact of cold clouds on simulations of climate. Global climate model (GCM) equilibrium climate sensitivity (ECS) can be up to 1.3°C higher if mixed-phase clouds are constrained by satellite observations, an impact linked to weakened cloud feedback (Fig. 4.6, Tan et al. 2016). The ratio of liquid to ice in high-latitude mixed-phase clouds, typically underestimated in climate models, plays a significant role in the cloud-phase feedback. Correcting this bias can reduce arctic amplification, although the effect is very sensitive to the cloud particle sizes (Tan and Storelvmo 2019). McCoy et al. (2015) found that the response of liquid water path in cold clouds to global warming in climate models was dependent on the assumed liquid-ice partitioning as a function of temperature and suggested that evaluation and validation of mixed-phase parameterization schemes against observations could substantially help reduce uncertainty in climate models. The representation of mixed-phase clouds impacts downwelling longwave radiation in the Arctic, which can then influence the thickness of winter ice and surface temperatures (Engstrom et al.

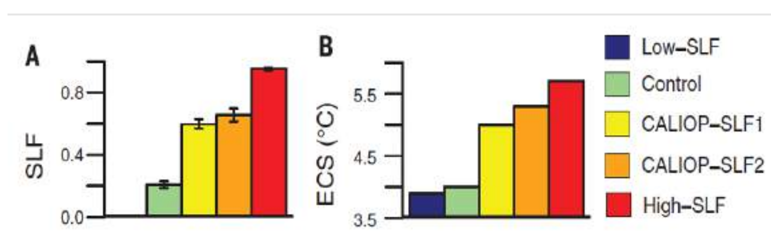


Figure 4.6. Illustration of the Equilibrium Climate Sensitivity (ECS) of climate simulations to supercooled liquid fraction (SLF), from Tan et al. (2016). (a) Initial extratropical SLF at –10°C and (b) ECS in response to a doubling of CO2. "Control" represents the default model case. The CALIOP cases represent two estimates constrained by CALIOP observations. The Low and High cases are specified levels of SLF. (Adapted from Tan et al. 2016)

2014). Model biases in mixed-phase clouds also impact simulations of wintertime Arctic temperature inversions (Pithan et al. 2014). McIlhattan et al. (2017) show that simulated mixed-phase clouds precipitate much more than observed, indicating that snow formation processes may be too strong in some models.

Measurements of atmospheric snowfall rates near the surface are highly uncertain but are important to hydrological balance, ice mass balance at high latitudes, and to water resources. Snowfall accounts for only 5% of all precipitation globally (Levizzani et al. 2011) but is the main source of precipitation in polar regions (ESA 2004, Fig. 4.7). Snowfall represents the major source of ice mass for ice sheets. The future of these ice sheets will be dependent on changes in precipitation intensity and phase, with many climate projections anticipating increases in precipitation at higher latitudes, but decreasing ratios of snowfall to total precipitation (Feng and Hu 2007; Kapnick and Delworth 2013; O'Gorman 2014) due to warming in regions with marginal cold temperatures (-14 to 0°C), typically at low to midlatitudes. Moreover, changes in arctic sea ice and lake ice may potentially impact the occurrence of heavy snowfall events (Burnett et al. 2003; Liu et al. 2012). While model reanalyses generally agree on the spatial distribution of precipitation at higher latitudes, total precipitation amount can vary by about 25% and interannual variability can be quite different (Boisvert et al. 2020).

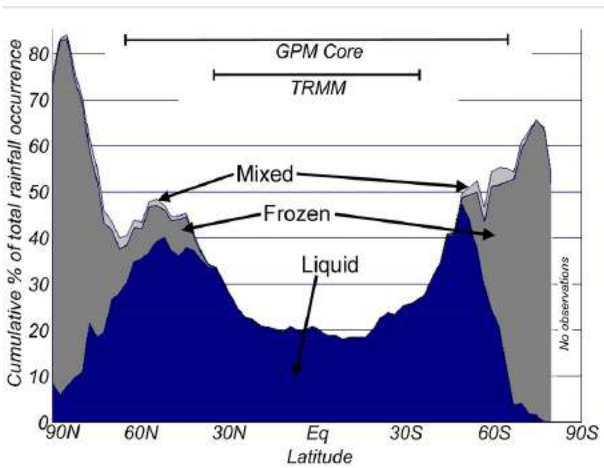


Figure 4.7. Mean occurrence of oceanic precipitation (as a percentage of total rainfall occurrence, 1958–1991) for liquid, ice, and mixed phase. The latitude ranges on top refer to the coverage of TRMM and GPM. (Adapted from ESA 2004, courtesy of C. Kidd)

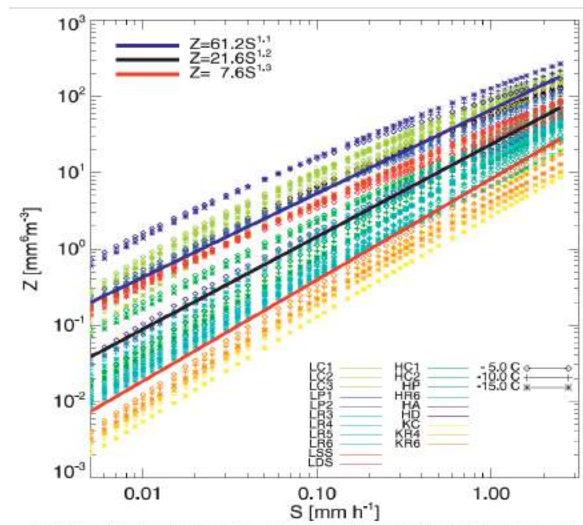


Figure 4.8. Sensitivity of the reflectivity-to-snowfall rate relationship to assumed particle properties (From Hiley et al. 2011). Each line represents a different assumed particle type at different temperatures (–5, –10, 1-5°C).

In order to predict how snowfall patterns might change in the future, it is not sufficient to simply know how snowfall accumulation changes but also to understand the atmospheric processes that underlie these changes. This means understanding the quantities, profiles, and properties of frozen (and mixed phased) precipitation in the context of the meteorological environment, orography, and surface properties. Estimating snowfall from space, however, can present some major challenges. Dry snowfall estimates can vary by an order of magnitude depending on particle type (Fig. 4.8, Kulie and Bennartz 2009, Hiley et al. 2011). Supercooled liquid water (SLW) layers can further confound retrievals, although Battaglia and Panegrossi (2020) suggest that combined active-passive approaches may better enable detection of SLW layers and their impacts on snowfall rate retrievals. Measurements by CloudSat saturate at several mm per hour while the GPM Dual-frequency Precipitation Radar lacks the sensitivity needed to measure light snowfall (Kulie and Bennartz 2009, Adhikari et al. 2018). Snowfall measurements from both missions near the surface are problematic due to surface clutter effects and can lead to missed snowfall from shallow clouds or phase transitions close to the surface.

4.4.2 Processes and variables

The collection of geophysical variables that are central to the O4 objective is highlighted in Table 4.4. This objective is highly complementary to objectives O1 (low clouds) and O8 (aerosol indirect effects) in that cold clouds, including low clouds and deeper cloud systems, play an important role in determining climate sensitivity and that improvement of the representations of cold clouds in Earth system models ultimately rests on advancing understanding of cloud-system properties, precipitation mechanisms, and radiative characteristics. The primary minimum geophysical variables important to this objective are the ice and liquid water paths, profiles of precipitation rate and phase, and associated radiative properties. Key enhancements include in-cloud cloud vertical air motion, advanced microphysical properties including precipitation particle size and density, and to the extent possible, profiles of ice and liquid water content. ACCP seeks to place these observations into the context of environmental conditions and surface properties, e.g., land vs. ocean, orography, surface fluxes.

Table 4.4. Key ACCP geophysical variables and science advances for O4. Acronyms include Tb, brightness temperature; SW, shortwave; LW, longwave; VIS, visible; NIR, near infrared; MV, microwave, CRE, cloud radiative effects; TOA, top of the atmosphere; sfc, surface; PoR, Program of Record.

Variable (minimum)	Variable (enhanced)	Measurement advances of A-Train	Transformative
	Vertical air motion (>1 ms^{-1})	W-band Doppler radar, >0.5m/s	Vertical motion at 0.5 m/s
Ice water and liquid water paths		Multi-frequency radar dBZ and brightness temperature (Tb), sub-mm MW radiometer	Combined active-passive retrieval on identical footprints
	Ice and liquid water content profiles	Lidar, multi-frequency radar dBZ, and Tb, sub-mm MW radiometer	Combined active-passive retrieval on identical footprints
Precipitation rate and phase		Radar profiling closer to surface, W-band Doppler	Profiling of low clouds, detection of phase changes to near surface
	Particle size and density	Multi-frequency radar dBZ and Tb, sub-mm MW radiometer	Combined active-passive retrieval on identical footprints
Cloud optical properties — bulk & profile		SW VIS & NIR spectral	Coincident cloud-scale cloud and radiative properties
LW & SW cloud radiative effects (CRE) (TOA)	LW&SW CRE (sfc)	SW VIS & NIR spectral, LW spectral	Spectral radiation budget @ cloud scale radiation kernels
Environmental and diurnal properties		PoR (e.g., geo. satellite), analyses	

4.4.3 Context

The study of mixed-phase and frozen clouds and precipitation will benefit greatly from the synergistic use of ACCP observations with the PoR expected at the time of the observing system. Rapid evolution of cloud properties will be dependent on the ring of geostationary satellites (Box GEO) but will be of limited value at high latitudes where the parallax problems become large. Additional cloud property information would be derived from JPSS VIIRS and METOP SG 3MI, METimage, and ICI. The ICI instrument will have sub-millimeter passive microwave channels (at 183, 243, 325, 448 and 664 GHz) that will be very complimentary to the ACCP radiometers (118, 183, 240, 310, 380, 660, 880 GHz) for measuring ice water path, snowfall, and ice cloud properties. Measurement of precipitation in a manner similar to GPM requires a robust constellation of passive microwave radiometers; this constellation is expected to include JPSS ATMS, METOP SG MWS and MWI, and the DoD WSF radiometer. Their integration into Earth System models through data assimilation, informed by active profiling by ACCP, can provide the basis for future global precipitation products. In addition to the cloud and precipitation measurements, environmental thermodynamic profiles will be essential for delineating liquid from frozen/mixed-phased conditions. This information can come from satellites such as JPSS ATMS and CrIS and METOP MWS and IASI, but most likely would come from assimilated products from reanalysis that incorporate the satellite observations.

4.4.4 Key advances

ACCP provides a significant advancement over existing heritage measurements such as from the A-Train and GPM for addressing cold-cloud systems and processes, offering measurements that are likely to be transformative for this topic. Table 4.4 summarizes key advances that are expected to occur on selected variables given the measurements being proposed. While the ACCP W-band radar will not be as sensitive as CloudSat (–25 vs –30 dBZ above the surface clutter zone, respectively), it offers several key advantages. First, with its much shorter pulse width, it will enable profiling of precipitation down to several hundred meters above the surface. The W-band radar will also have a slightly smaller footprint, ~1.1x0.9 km for ACCP versus 2.5x1.4 km for CloudSat. Doppler capability using a Displaced Phase Center Antenna (DPCA) approach will reduce Doppler noise and bias due to non-uniform beam filling, providing Doppler accuracy of ~0.5 m s^{-1}. Doppler measurements will be valuable for phase determination as well as estimates of vertical air motion. The W-band radar will also be coupled with a Ka-band radar in polar orbit, allowing for measurement of heavier precipitation rates. Dual-frequency retrievals will be possible for reflectivities above ~0 dBZ (the sensitivity at Ka band). Finally, the radars will provide passive capability with precision of ≤1 K, which will allow for combined active-passive retrievals at the radar footprint scale for improved constraints on ice and liquid water path. Ice water path retrievals will also benefit from joint radar-lidar-sub-millimeter passive microwave radiometer measurements.

ACCP will also deliver cloud microphysical properties that are a substantial advance on capabilities today along with collocated cloud-scale radiative flux information. The microphysical properties include size distribution (size and concentration) and shape (aspect ratio, roughness) information at cloud top and precipitation particle size and density within the clouds. The dynamical context provided by ACCP measurements is also transformative, including the Doppler measurements mentioned above and cloud-top motion information from time-differenced stereo camera measurements, which will offer unique opportunities to address cloud-top processes, including that of entrainment, in cold low clouds.

4.5 Objective O5: Aerosol Attribution and Air Quality

Underlying science questions: What are the major anthropogenic and natural sources of aerosol and how do they vary spatially and temporally? What are the factors that relate aerosol microphysical and optical properties to surface PM concentrations? To what extent does long-range transport of smoke, dust, and other particulates impact regional near-surface air quality?

Minimum: Quantify optical and microphysical aerosol properties in the PBL and free troposphere to improve process understanding, estimates of aerosol emissions, speciation, and predictions of near-surface particulate concentrations.

Enhanced: Characterize variations in vertical profiles of optical and microphysical properties over space and time in terms of 3D transport, spatially resolved emission sources and residual production and loss terms.

4.5.1 Rationale

Along with tropospheric ozone and other reactive gases, aerosols determine the quality of the air we breathe, with implications for human health (e.g., US EPA 2016; OECD 2016; Lim et al. 2012), life expectancy and the health of terrestrial and marine ecosystems. Natural and anthropogenic aerosols also affect the safe operation of transportation systems, the generation of solar power (section 5), in addition to clouds, convection and precipitation and the Earth's radiation budget (e.g., Boucher et al. 2013). The impacts of aerosols on climate, human health, transportation, and other applications strongly depend on the composition of particles.

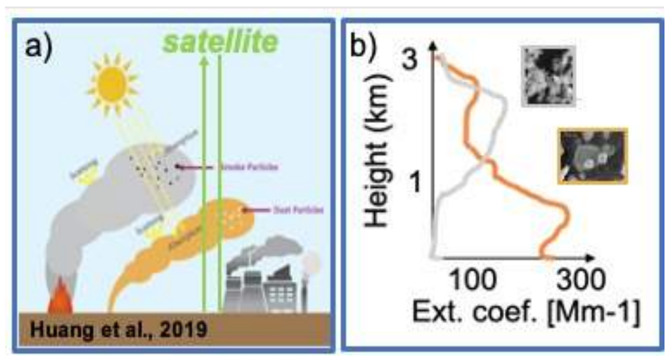


Figure 4.9. (a) Dense smoke plume overlaying a dust layer in the vertical atmosphere (adapted from Huang et al. 2019) and (b) satellite-derived extinction coefficient profiles corresponding to these two types of aerosols. Particle images from https://earthobservatory.nasa.gov/features/Aerosols and https://www.hcn.org/issues/46.22/the-dust-detectives.

In order to predict and quantify these impacts, and the processes that determine aerosol distributions, vertically resolved measurements of aerosol microphysical properties near the surface and in the free troposphere are required. Those measurements ought to possess sufficient information content as to discern the contributions from different aerosol components, leading to improved estimates of the underlying aerosol emissions.

The primary rationale for this objective is to recognize the importance of quantifying and vertically resolving aerosol properties in the atmosphere (illustrated by Fig. 4.9), in order to constrain, evaluate and improve predictions and process understanding. The *minimum* science objective relates to the attribution of aerosols to their sources, a measure of aerosol size, shape (spherical or non-spherical) and fundamental optical properties such as the index of refraction of individual components or mixtures. Such measurements ought to enable improved estimates of empirical aerosol type characterization (e.g., aerosol types derived by POLDER or CALIPSO, or more detailed speciation aided by data assimilation in chemical transport models). Aerosol attribution within the vertical column is essential to address many ACCP science objectives (i.e., Objectives O3, O5, O6, O7, and O8). Except for profiles of aerosol extinction, the *minimum* objective requires most properties provided in specific layers, be it within the Planetary Boundary Layer (PBL), the free troposphere and in some cases the full atmospheric column.

The *enhanced* science objective adds to the *minimum* with vertical profiles of most aerosol optical and microphysical properties, and the characterization of the variation of these properties in terms of 3D transport, spatially resolved emission sources and residual production/loss terms.

4.5.2 Processes and variables

Aerosol source attribution, and more specifically fine tuning of emissions by means of inverse calculations can be inferred from the combination of aerosol optical and microphysical properties provided by ACCP and the PoR. Successfully addressing this objective rests on the accurate quantification of optical and microphysical aerosol properties within the vertical profile/layers, with particular emphasis on the PBL where emissions are first injected. The Total atmospheric Column (TC) measurements afforded by the passive instruments, while not vertically resolving the aerosol properties, provide spatial context and an important constraint on the remote transport of the emitted aerosol plumes and are useful for inverse estimates of aerosol sources. Constraining aerosol properties near the surface is particularly important to determine nose-level $PM_{2.5}$ (Particulate Matter with an aerodynamic diameter of 2.5µm, see section 5.2) for air quality applications, and to advance the understanding of the processes controlling these concentrations.

The *minimum* objective requires observations that can inform on the aerosol loading, shape (e.g., spherical vs. non-spherical) and size in the vertical profile (e.g., total and non-spherical aerosol extinction coefficient profile and the ratio of aerosol extinction at two wavelengths), and on the aerosol's ability to absorb solar radiation within the TC and PBL (e.g., the absorption optical depth and the ratio of extinction to backscatter coefficient). Aerosol intensive optical and microphysical properties that require more assumptions in their retrieval (e.g., aerosol refractive index within the TC and PBL) will help further constrain the aerosol attribution.

The *enhanced* part of this objective relies on quantifying aerosol optical and microphysical properties in the vertical profile (e.g., aerosol effective radius, absorption, ratio of extinction to backscatter coefficient). Near-surface $PM_{2.5}$ is critical to address air quality but is one of the most challenging geophysical variables to derive from space, as it requires information on the near-surface relative humidity, aerosol hygroscopicity, extinction, mass extinction efficiency, and fine mode fraction.

4.5.3 Context

Currently, the majority of sensors in space that are passively observing solar reflection are either in polar sun-synchronous or geostationary orbit. Certain sensors in polar orbit provide products representing intensive (e.g., single scattering albedo and/or type from TOMS, OMI, OMPS, TropOMI and MISR) and extensive (e.g., total column aerosol optical depth from MODIS, VIIRS and MISR) aerosol properties. While these sensors determine extensive aerosol properties reasonably well, they do not possess the necessary information content to adequately constrain aerosol intensive properties. Among the polar orbiter sensors listed above, only OMPS, TropOMI and VIIRS are likely to continue into the ACCP timeframe.

Observations of aerosol global distribution and transport during the day from geostationary multispectral radiometers ABI/GOES R-U, AHI/Himawari, AMI/KOMPSAT 2A and FCI/Meteosat MTG-11-14 will provide context for the advanced aerosol properties from ACCP. In addition, geostationary spectrometers UVNS/Sentinel-4, GEMS/KOMPSAT 2B and TEMPO will provide global observations of atmospheric composition, including aerosols. In particular, they will carry sensors with channels in the oxygen A-band which are sensitive to aerosol layer height. This operational aerosol height information will provide spatial and temporal context to the much more detailed vertical information from the ACCP lidar(s). Further, the ACCP lidar(s) will provide detailed aerosol profiles useful for validation and interpretation of these passive layer height retrievals. Geostationary sensors ABI, AHI, AMI, FCI and UVNS are likely to continue into the ACCP timeframe.

Multiple studies highlight the potential of spaceborne polarimetry to improve retrievals of aerosol properties such as amount, size and index of refraction. Furthermore, combining active and passive polarimetric (and multi-angular) remote sensing will greatly improve the detection and accurate quantitative characterization of tropospheric aerosols. The space-based polarimetry aerosol record began with POLDER-3/PARASOL from 2005 to 2013. More recently, HARP, an imaging polarimeter onboard a 3U CubeSat spacecraft, has been flying since April 2020. Within the next few years, there will be multiple polarimeters including MAIA/OTB, HARP2/PACE and SPEXOne/PACE and finally, the 3MI/Metop-SG mission. CALIOP/ CALIPSO, an elastic backscatter lidar, is currently the only active spaceborne sensor providing aerosol backscatter and inferring extinction profiles in the visible and near infrared in both cloud-free and cloudy conditions. The next lidar in space is ATLID/EarthCare, a High Spectral Resolution Lidar (HSRL) operating in the ultraviolet range. Polar orbiter sensors MAIA, HARP2, SPEXOne, 3MI, and ATLID are scheduled to launch in the 2023 timeframe. Among these polarimetric and active sensors, only 3MI is likely to continue into the ACCP time frame and is likely to have lower performance than the polarimeter instrument(s) intended for ACCP.

4.5.4 Key advances

Table 4.5 summarizes key advances on selected variables that will have high impact in achieving this objective. ACCP will deliver advancements beyond the past and current spaceborne sensors by quantifying the aerosol optical and microphysical properties within the vertical atmosphere using a combination of space-borne polarimeter(s), lidar(s), and spectrometer(s) pointing at the same volume. These observational constraints when combined with significant advancements in modeling, data assimilation and the PoR will make significant contributions to process understanding, estimates of aerosol emissions, speciation, and predictions of near-surface particulate concentrations. Additionally, the improved speciation of $PM_{2.5}$ will allow investigation linkages between aerosol species and human health and other applications as outlined in section 5.

ACCP suborbital efforts will play a major role in enhancing the ACCP orbital observations (e.g., quantitatively inform on the aerosol chemical speciation or the near-surface speciated $PM_{2.5}$) by providing validation of orbital retrievals, characterization of optical and microphysical properties of chemical species that are represented in models and investigating near-surface processes involving air quality (section 6.3).

Table 4.5 Key ACCP geophysical variables and science advances for Objective O5. Acronyms include UV, ultraviolet; VIS, visible; NIR, near infrared; VP, vertical profile; TC, total column; PBL, planetary boundary layer.

<table>
<tr><th>Variable (minimum)</th><th>Variable (enhanced)</th><th>Measurement advances of A-Train</th><th>Transformative</th></tr>
<tr><td>Aerosol Total and Non-Spherical Extinction
(VIS & NIR; VP)</td><td>Aerosol Total Extinction
(UV; VP)</td><td rowspan="2">The ACCP backscatter lidar on the inclined orbit will be an improvement over CALIOP and provide diurnally resolved measurements.

The ACCP HSRL* lidar in the polar orbit will be the first ever VIS lidar of its kind in space.</td><td rowspan="4">Significant improvements of key aerosol variables and vertical profile of optical and microphysical measurements</td></tr>
<tr><td>Aerosol Extinction to Backscatter
(TC & PBL)</td><td>Aerosol Extinction to Backscatter
(VP)</td></tr>
<tr><td>Aerosol Absorption Optical Depth
(UV & VIS; TC & PBL)</td><td>Aerosol Absorption
(UV & VIS; VP)</td><td rowspan="2">Combined+ polarimeter** and lidar pointing at the same volume</td></tr>
<tr><td>Aerosol Fine Mode Optical Depth
(TC & PBL)</td><td>Aerosol Effective Radius (VP)</td></tr>
<tr><td colspan="4">* HSRL improves on near-surface backscatter and extinction which is important for air quality and aerosol attribution; ** Polarimeter improves on total column AOD, and provides column retrievals of aerosol absorption optical depth, single scattering albedo, refractive index for aerosol attribution and water content; + Combined polarimeter and lidar provide layer-resolved values of the above parameters; the lidar can unambiguously identify the scene (e.g., altitude of aerosol or cloud layers) and provide constraints on the polarimeter retrieval.</td></tr>
</table>

Finally, the minimum and enhanced part of this objective require (i) a polar orbit for maximum geographic coverage and to capture aerosol transport to the polar regions and (ii) aerosol retrievals at high vertical (<100 m) and horizontal (< 25 km) resolution to resolve aerosol optical properties in the PBL and free troposphere, especially over land for human health applications; the aerosol attribution part of this objective is equally important over land and ocean. Aerosol diurnal observation (from geostationary satellites and/ or limited coverage of the diurnal cycle in the case of an inclined orbit) provides valuable information on consequences of processes linked to the diurnal evolution of the boundary layer and would be particularly useful to constrain emissions of specific aerosols with a strong diurnal cycle (e.g., smoke, traffic exhaust).

4.6 Objective O6: Aerosol Wet Removal, Vertical Redistribution and Processing

Underlying science questions: What are the factors that control the spatial distribution aerosol microphysical and optical properties? To what extent does long-range transport of smoke, dust, and other particulates impact regional near-surface air quality?

Minimum: Relate the vertical structure of aerosol properties to cloud and precipitation properties to improve understanding of processes impacting aerosol vertical transport, removal, and overall lifecycle in light and moderate precipitation regimes (< 5 mm/hr).

Enhanced: Extend minimum to include heavy precipitation regimes (> 5 mm/hr), aerosol processing (including gaseous and aqueous production) and vertical transport to UTLS region.

4.6.1 Rationale

Aerosols, cloud particles, vertical motion, precipitation, and radiation are integrally linked (Fig. 4.10) and these strong linkages were the main motivation for the ACCP study to combine the *Aerosol* and the *Cloud, Convection and Precipitation* Designated Observables recommended by the 2017 Decadal Survey. Aerosol affects the formation and subsequent evolution of clouds and precipitation, while the air motion within clouds transports aerosols in the vertical and precipitation wash-out is one of the main aerosol removal mechanisms. The impact of aerosols on clouds and precipitation is considered in ACCP objectives O1, O2, O3 and O8. Objective O6 explicitly focuses on the impact of clouds and precipitation on aerosols.

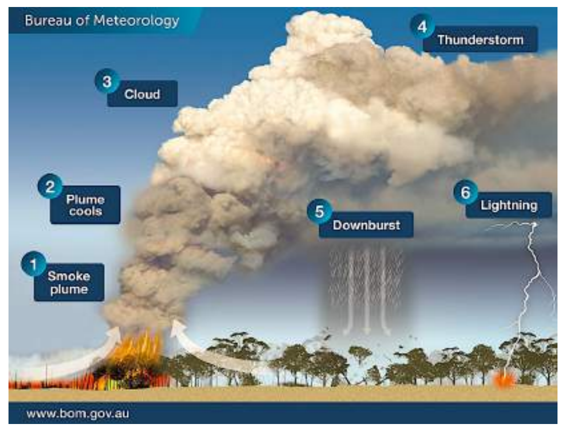


Figure 4.10. The storms developing in association with recent fires demonstrate links between vertical motion, aerosols, cloud and precipitation processes. From https://media.bom.gov.au/social/blog/1618/when-bushfires-make-their-own-weather/

Comprehensive Earth-system models used for weather, air-quality and climate predictions include atmospheric constituents (aerosols, greenhouse, and reactive gases) and their interactions with the circulation. These models inform past, present and future location, loading and species of aerosols and their impact on the climate system. Representation of aerosol processes in models, most notably processing by clouds and microphysical processes that remove and transport aerosols remains a great source of uncertainty. The lack of near simultaneous vertically resolved observations of aerosols, clouds and precipitation microphysical properties on a global scale have hampered progress in this area. The ACCP constellation is designed to provide the necessary missing measurements to further the understanding of such processes leading to improved models and enhanced predictability.

4.6.2 Processes and variables

Figure 4.11 illustrates the typical lifecycle of aerosols within clouds. Aerosols emitted at the surface are transported into the cloud by upward vertical motion at the cloud base, or by lateral entrainment of aerosols of possible remote origin. Within the cloud, aerosols can continue to experience vertical transport and undergo further processing such as hygroscopic growth, activation of water droplets and ice particles, aqueous chemistry, and scavenging in the presence of precipitation, with detrainment at upper levels. Understanding these complex processes require detailed measurements of cloud and aerosol microphysical properties. While simultaneous aerosol microphysical measurements inside clouds are not possible from space, near-simultaneous measurements will provide significant information to constrain the behavior of models, with the ACCP suborbital component providing the simultaneity of measurements that is needed to advance process understanding. While ACCP is not designed to specifically address the aerosol aqueous chemistry problem, concurrent use of the trace gas measurements from the polar orbiting and geostationary PoR (e.g., TROPOMI, GEMS, TEMPO and their successors), when combined with ACCP detailed microphysical measurements, will provide new insights on aerosol processing within clouds.

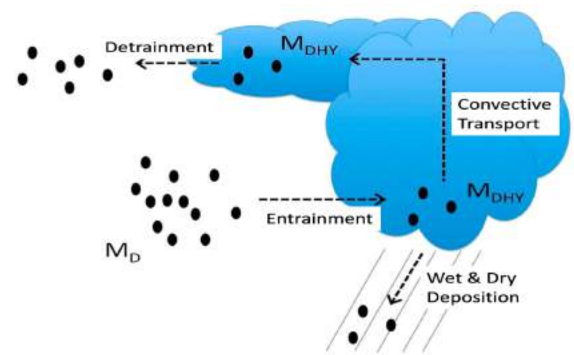


Figure 4.11. Aerosols processes in clouds. Adapted from Herberner et al. (2016).

Understanding the impact of clouds and precipitations on aerosol distribution requires most of the same fundamental microphysical measurements that are need for addressing cloud feedbacks (O1, O2), convection (O3), air-quality (O5) as well as aerosol radiative impacts (O7, O8). A summary of the key geophysical variables is outlined in Table 4.6. The *minimum* objective calls for characterizing the cloud and moderate precipitation environment (cloud effective radius, precipitation rate and phase), along with fundamental aerosol properties (aerosol extinction profile, column and PBL estimates of fine and total AOD, aerosol effective radius.) Such variables will permit composite analysis of before, during and after moderate precipitation events advancing studies performed with the very limited EOS-era observing system (CALIOP and MODIS, *e.g.,* Sauter et al. 2017). To address the *enhanced* portion of the objective, additional profiles of in-cloud vertical air velocity, precipitation particle size, profiles of heavy precipitation events, as well as detailed profiles aerosol properties (UV extinction profile for better aerosol attribution, fine mode fraction and effective radius) are required. Such detailed measurements will permit a more detailed delineation of processes in the vertical and extend the analysis to deep convective events.

4.6.3 Key advances

The key advances and transformative elements of ACCP for O6 are summarized in Table 4.6. The ACCP backscatter Lidar on the inclined orbit will be an improvement over CALIOP and provide diurnally resolved measurements. The ACCP HSRL Lidar in the polar orbit will be the first ever VIS Lidar of its kind in space, and when combined with concurrent polarimeter measurements, will provide unprecedented characterization of vertically resolved aerosol properties. Measurements from the multi-frequency Doppler radars and radiometers (including sub-mm brightness temperature) will enable synergistic active-passive retrievals of profiles of small to large hydrometeors and motion in light to heavy precipitation through the atmospheric column. Such a comprehensive aerosol-cloud-precipitation observing system will provide new and exciting measurements to improve the representation of aerosol wet removal, vertical redistribution and, when combined with the trace-gas PoR, aerosol processing needed by the Earth-system models that will be available by the end of the decade.

Perhaps to an even larger extent than for other objectives, the ACCP suborbital component will be critical to fully address this objective. Besides the traditional role of validating retrievals within and outside clouds, segments of the ACCP suborbital campaigns will be designed to address the inherent challenge of simultaneously observing clouds and aerosols from space (section 6.3).

Table 4.6. Key ACCP geophysical variables and science advances for O6. Acronyms include MF, multi-frequency; Tb, brightness temperature; HSRL, high-spectral resolution lidar; PBL, planetary boundary layer; PoR, Program of Record.

Variable (minimum)	Variable (enhanced)	Measurement advances over A-Train	Transformative
Cloud effective radius Profile		SW VIS & NIR spectral	Number concentration and profile of effective radius
	In-cloud vertical air velocity $\lvert>2\ ms^{-1}\rvert$	Multi-frequency (MF) (e.g. Ku/Ka/W) Doppler radar profiling	Vertical motion in convective storms at convective scale footprints
Precipitation rate profile < 2mm/hr	Precipitation rate profile > 2mm/hr	MF (e.g., Ku/Ka/W) Doppler radar profiling and Tb w/sub-mm microwave radiometer	Combined active-passive retrieval with hydrometeor Doppler velocity constraint on identical footprints
Precipitation phase Profile Near surface included		MF (e.g., Ku/Ka/W) Doppler radar profiling and Tb w/sub-mm microwave radiometer	Profiling of small to large hydrometeors and motion in light to heavy precipitation through cloud column
	Precipitation Particle size	MF (e.g., Ku/Ka/W) Doppler radar profiling and Tb w/sub-mm microwave radiometer	Combined active-passive retrieval with hydrometeor Doppler velocity constraint on identical footprints
Aerosol Extinction Profile VIS & NIR	Aerosol Extinction Profile UV		
Aerosol Fine Mode optical depth Column, PBL	Aerosol Fine Mode Extinction Profile	HSRL Lidar, polarimeter	More accurate aerosol profile
Aerosol Optical Depth Column, PBL		HSRL Lidar, polarimeter	More accurate aerosol profile
Aerosol Effective Radius Column, PBL	Aerosol Effective Radius Profile		

4.7 Objective O7: Aerosol Direct Effects and Absorption

Underlying science questions: How do changes in anthropogenic aerosols affect Earth's radiation budget and offset the warming due to greenhouse gases? What is the role of absorbing aerosols in the Earth's radiation budget and thermodynamics?
Minimum: Reduce uncertainties in estimates of: 1) global mean clear and all-sky shortwave direct radiative effects (DRE) to ±1.2 W/m2 at TOA and the anthropogenic fraction, 2) regional TOA and surface DRE, and 3) Quantify the impacts of absorbing aerosol on atmospheric stability.
Enhanced: Quantify the impact of absorbing aerosols on vertically resolved aerosol radiative heating rates and DRE commensurate with the uncertainties in global mean at TOA and surface.

4.7.1 Rationale

Anthropogenic aerosols are responsible for significant impacts on the global energy budget. Uncertainties associated with aerosol radiative forcing (ARF) estimates are among the leading causes of discrepancies in climate simulations and the large uncertainties in the total anthropogenic effective radiative forcing (ERF) (IPCC 2013). The radiative forcing due to anthropogenic aerosols is highly uncertain (Fig. 4.12) resulting in large uncertainties in model projections of temperature and precipitation changes as well as equilibrium climate sensitivity. Reductions in co-emitted anthropogenic aerosols associated with mitigation of greenhouse gases will likely result in significant changes in temperature, precipitation, and extreme weather, particularly for populated regions (Samset et al., 2014). There is considerable observational (Loeb and Su 2010, Bellouin et al. 2013, Thorsen et al. 2021) and modeling evidence (Samset et al. 2014) that the latest IPCC uncertainty in global ARF is underestimated. A reduction of current observational uncertainties and improvements in models are necessary for the historical record to provide useful constraints on the upper end of climate sensitivity (Sherwood et al. 2020). The satellite-based observational anthropogenic estimate of TOA SW DARE is often simply derived by selecting only fine mode dominant particles. ACCP will not only provide more accurate size information (e.g., effective radius) but also additional information on composition, which will help distinguish anthropogenic from natural sources of fine particles.

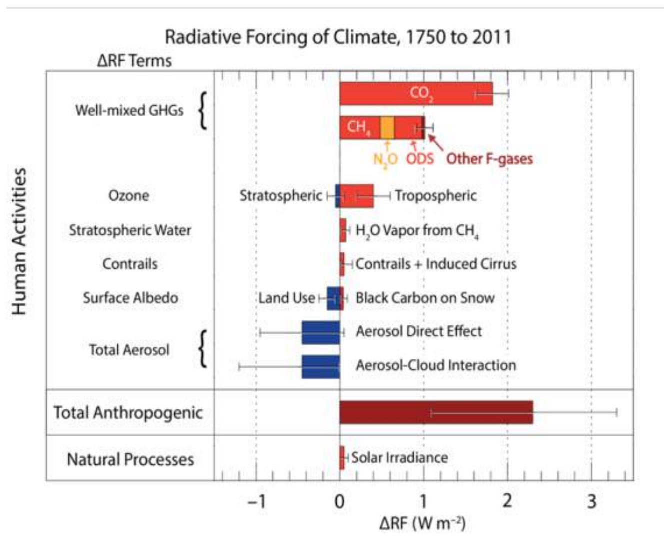


Figure 4.12. Contributors to radiative forcing (IPCC 2013).

Current observational estimates of aerosol DRE forcing are too uncertain to provide a significant constraint on modeled estimates (Thorsen et al. 2021). Therefore, this objective seeks to provide observation-based constraints with uncertainties comparable to and ideally smaller than those reported in the IPCC Fifth Assessment Report (AR5, Boucher et al., 2013). The threshold goal would provide a significant improvement (by about a factor of 3) over the current estimates of clear-sky ocean DRE (Yu et al. 2006, Oikawa et al. 2013, Matus et al. 2015, Oikawa et al. 2018) and would provide estimates over land and in cloudy columns that currently have large uncertainties.

The enhanced objective seeks to quantify the impacts of the vertical structure, and in particular aerosol absorption, on radiative effects and heating rates. Understanding the optical (scattering, absorption) properties as well as the vertical position of aerosol layers will improve estimates of aerosol radiative effects at the surface and within the atmosphere and help quantify the impacts of absorbing aerosols on atmospheric heating rates. This aerosol heating in turn impact cloud properties and lifecycles; consequently, this objective ties into objectives O1 and O8.

4.7.2 Processes and variables

This objective's goals are framed in terms of the annual-mean global-mean aerosol DRE. At present, there are several well-established radiative transfer models (Mlawer et al. 1997, Clough et al. 2005, Rose et al. 2013) that can compute the aerosol DRE at the TOA, surface or anywhere within the atmosphere. The challenge lies in providing accurate inputs for these forward calculations; uncertainty in the inputs themselves will likely continue to dominate the uncertainty budget even with the improved accuracies provided by ACCP. Additionally, a SW spectrometer provides alternative/complementary measurements of the DRE to this forward model approach (Loeb and Kato 2002, Loeb and Manalo-Smith 2005).

Aerosol scattering and absorption properties over all surface types (land and ocean) and in all-sky conditions (i.e., clear-sky, below thin cloud and above cloud) are needed to make truly global estimates of DRE. For the most part, the threshold objectives require column-averaged aerosol properties such as aerosol optical thickness, aerosol absorption optical depth, and an effective asymmetry factor in the mid-visible. For the most part, the threshold objectives require column-averaged aerosol properties such as aerosol optical thickness, aerosol absorption optical depth, and an effective asymmetry factor in the mid-visible. These properties would be desired in clear skies, and layer-averaged values would also be desired above thick cloud and under thin clouds. Although the direct measurement of heating rate from space is not possible, the heating rate by aerosols can be computed when the aerosol extinction coefficient, single scattering albedo, and phase function or asymmetry parameter are retrieved. Spectral closure studies using the SW spectrometer will be used to evaluate the input aerosol parameters and the computed DRE products. Observed broadband flux observations will also be available from the PoR for comparison.

4.7.3 Key advances

Current satellite sensors have begun providing quantitative spatial distributions of aerosol optical thickness (e.g., MODIS, MISR, VIIRS), aerosol backscattering in the vertical (e.g., CALIPSO, CATS), aerosol absorption (OMI) and some information on size, and shape. However, the accuracy of these measurements is insufficient for reducing ARF uncertainties to an acceptable level. Even in the best cases, current satellite sensors measure aerosol optical depth (AOD) to within about ±0.04 (at ~500 nm) (Fig. 4.13) (Sayer et al. 2018). This AOD uncertainty is inadequate to reduce the uncertainties in estimates of aerosol direct radiative forcing and constrain advanced aerosol transport models. The usefulness of CALIPSO daytime profiles of aerosol backscattering and extinction are limited by SNR, by necessary retrieval assumptions, and do not retrieve all radiatively significant aerosol (Rogers et al. 2014, Thorsen and Fu 2015, Thorsen et al. 2017). Vertically resolved aerosol absorption, a key parameter controlling radiative forcing within the atmosphere, is particularly difficult to measure from space so that atmospheric models rely primarily on ground based AERONET retrievals of absorption, which are limited to certain land sites, and are restricted to relatively high (AOD>0.4 at 440 nm) AOD cases. Other sources of global aerosol absorption constraints, such as satellite retrievals in the UV (e.g., TOMS, OMI) or multi-angle, multi-spectral (MISR) plus polarimetric (POLDER) retrievals, tend to be coarse resolution (TOMS, OMI) or qualitative (MISR). Direct, *in situ* sampling that provides detailed absorption information has extremely poor global coverage.

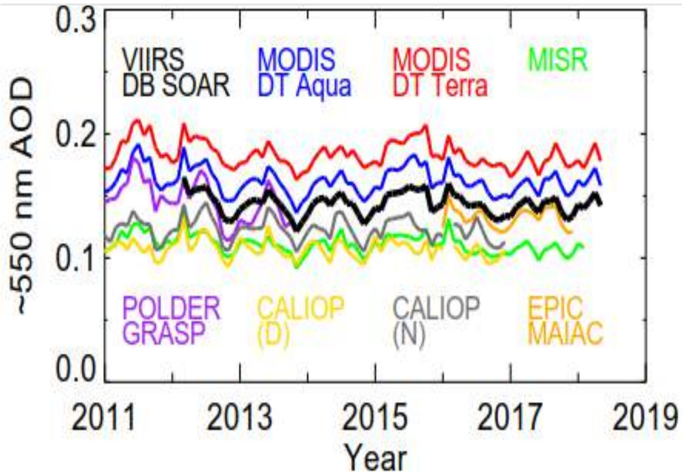


Figure 4.13. Global AOD Time Series (Sayer et al. 2018).

Key geophysical parameters desired for this objective and some key advances provided by ACCP sensors are shown in Table 4.7. Following the approach in Thorsen et al. (2020, 2021), we found that the reduction in global DRE uncertainties specified by this objective could be met provided that the ACCP instruments provide aerosol data (e.g. AOD, single scatter albedo (SSA), aerosol, type, aerosol extinction) that meet the minimum ACCP targets. ACCP seeks more accurate AOD measurements, especially over land, and more accurate measurements and retrievals of AAOD and SSA over both land and ocean. Current OMI satellite retrievals of AAOD and SSA typically provide retrievals only in the UV and only for elevated aerosol layers. In contrast, the ACCP measurements would provide not only additional information regarding aerosol type for more appropriate selections of the aerosol model and associated SSA but would also allow more accurate retrievals of SSA and AAOD. In addition to providing more accurate AOD over land and water at multiple wavelengths, layer-resolved aerosol properties (e.g. effective radius, absorption, fine mode extinction) over both land and water are enabled by combined lidar+polarimeter retrievals (Xu et al. 2021). Aerosol extinction profiles derived from the HSRL technique have much lower uncertainties than those derived from backscatter lidars such as CALIOP, particularly near the surface and under thin cirrus. In addition, these profiles do not require assumptions or additional information relating aerosol backscatter to extinction. Cloud properties (boundaries, optical depth and particle size) are needed to compute the aerosol DRE in cloudy columns and would be provided by ACCP instruments in conjunction with the PoR. Surface albedo and its spectral dependence will be characterized by spectrometer and polarimeter measurements.

Single daytime and nighttime sampling from a polar-orbiting satellite is sufficient for computing the diurnally averaged global aerosol DRE and AOD. Diurnal sampling of polar-orbiting satellites does not significantly impact the computation of diurnally averaged aerosol DRE or AOD for certain equatorial crossing times (e.g., TERRA and AQUA) (Kaufman et al. 2000, Arola et al.

2013, Kassianov et al. 2013). Sampling AOD using a single-pixel along-track satellite instrument causes only small biases in global monthly means (Geogdzhayev et al. 2013, Geogdzhayev et al. 2014), although more substantial errors can be found in regional means (Colarco et al. 2014).

Table 4.7. Key ACCP geophysical variables and science advances for O7. Acronyms include HSRL, high-spectral resolution lidar; AOD, aerosol optical depth; SW, shortwave; VIS, visible; NIR, near infrared.

Variable (minimum)	Variable (enhanced)	Measurement advances of A-Train	Transformative
Aerosol Optical Depth		HSRL and polarimeter provide AOD to ±0.02	
Aerosol Absorption Optical Depth	Aerosol Absorption Profile	Lidar/ HSRL+polarimeter	High accuracy; layer-resolved aerosol absorption
Aerosol Fine Mode Optical Depth		Lidar/ HSRL+polarimeter	Retrievals over land as well as ocean
Aerosol Extinction Profile	Aerosol Fine Mode Extinction Profile	HSRL profiles provide direct measurement	Tenuous aerosol; aerosol below thin cirrus; accurate near surface extinction
Aerosol Effective Radius	Aerosol Effective Radius Profile	Aerosol size	Layer-resolved aerosol size
Aerosol Refractive Index		Polarimeter/HSRL+polarimeter	Information regarding aerosol composition; water content
SW Aerosol Radiative Effects	SW radiative heating rate	SW VIS/NIR spectral	

4.8 Objective O8: Aerosol Indirect Effect

Underlying science questions: Under what conditions do aerosols impact the albedo or coverage of shallow clouds and by how much?
Minimum: Provide measurements to constrain process level understanding of *aerosol-warm cloud* interactions to improve estimates of aerosol indirect radiative forcing**.**
Enhanced: Provide measurements to constrain process level understanding of interactions of aerosol with *cold and mixed-phase clouds* to improve estimates of aerosol indirect radiative forcing**.**

4.8.1 Rationale

Uncertainties in anthropogenic forcing of the climate system are dominated by aerosol direct and indirect radiative effects (IPCC AR5) and the extent to which warming from greenhouse gases is offset by atmospheric aerosols is poorly constrained (Bellouin et al. 2020). Reducing current uncertainties was called out as one of the most important science priorities in the 2017 Decadal Survey report.

Objective 8 is concerned with the microphysical, radiative, and dynamical processes that couple clouds, precipitation, and radiation with the ambient environment and how they are modulated by aerosol to alter cloud radiation. Figure 4.14 indicates the wide range of aerosol sources, cloud types, and processes relevant to indirect radiative forcing of aerosols.

The O8 minimum objective focuses on the radiative consequences of aerosol microphysical and radiative interactions with warm clouds. ‘Warm clouds’ include stratus and shallow convective clouds which do not reach the freezing level, especially trade cumulus. The aerosol, cloud, and precipitation processes involved are poorly represented in climate models and better observations are required to guide model improvements. The O8 enhanced objective is concerned with aerosol impacts on ice and mixed-phase clouds, where progress will be more difficult due to numerous possible ice formation mechanisms. Aerosol impacts on deep convective clouds are covered by Objective 3.

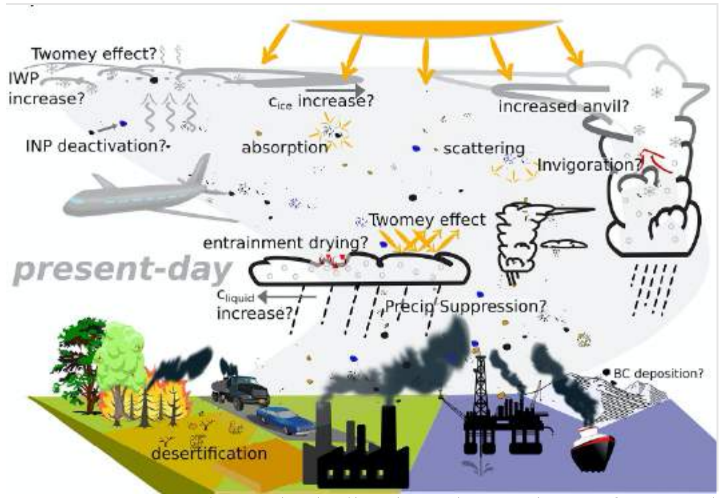


Figure 4.14. Schematic indicating the variety of aerosol sources, cloud types, and processes relevant to indirect radiative forcing by aerosols (Bellouin et al. 2019).

Objective 8 is also linked to Objective 1 and Objective 2. Modification of the parameterizations of aerosol-cloud interaction processes in CESM2 to match the 20th century temperature record also resulted in changes to simulated cloud feedbacks (Gettelman et al 2019). Thus, in the complex models used to simulate climate, aerosol indirect forcing and cloud feedbacks are not independent but are coupled due to the dependence of both on some of the same cloud processes. Objective 8 is primarily concerned with the short time scale (days) responses of cloud to microphysical and radiative interactions with aerosols, while O1 and O2 are more concerned with understanding the long-term response of clouds to environmental changes driven by climate change.

4.8.2 Processes and variables

The original formulation of the indirect aerosol effect was that increasing CCN concentrations cause cloud droplet concentrations to increase, with an associated decrease in cloud droplet size and increase in cloud brightness assuming cloud LWP is fixed (Twomey 1977). It was later recognized that increasing CCN concentrations may also lead to changes in LWP, cloud fraction, and other cloud variables as the outcome of perturbations of multiple coupled cloud processes (Stevens and Feingold 2009). Precipitation processes have recently been recognized as especially important in modulating or even reversing the sign of the impact on cloud albedo predicted by Twomey (Chen et al. 2014).

Aerosols can also impact clouds via radiative interactions. Warming from absorbing aerosol in the marine boundary layer can reduce relative humidity and suppress cloud formation (Ackerman et al. 2000). Aerosol above cloud tends to stabilize the atmosphere below and can also reduce surface evaporation, with impacts that depend on cloud type (convective vs. non-convective).

Reducing uncertainties in indirect radiative forcing requires a comprehensive suite of co-located observations of aerosol, cloud, precipitation, and radiation, as well as characterization of the environment within which clouds form. Process understanding will come from constructing a variety of metrics from ACCP observations which constrain processes at various levels of detail, from microphysical-oriented joint statistics to relations between high level parameters such as cloud fraction and all-sky albedo (Mülmenstädt and Feingold 2018).

Table 4.8. Key ACCP geophysical variables for addressing the aerosol indirect effect. Acronyms include HSRL, high-spectral resolution lidar; PBL, planetary boundary layer; SWIR, shortwave infrared; SW, shortwave; VIS, visible; LWP, liquid water path; IWP, ice water path.

Key Variables (minimum)	Key Variables (enhanced)	Measurement advances of A-Train	Transformative
Aerosol Absorption Optical Depth		HSRL+polarimeter	Layer-resolved aerosol absorption
Aerosol Fine Mode Effective Radius		HSRL+polarimeter	
Aerosol Extinction Profile	Aerosol Fine Mode Extinction Profile	Improved accuracy from HSRL	Tenuous aerosol; vertically-resolved aerosol size: effective radius, Å(z)
Cloud LWP	Cloud IWP	T_B from radar VIS-SWIR spectrometer	
Cloud Optical Depth		VIS-SWIR spectrometer	High spatial resolution bispectral retrievals
Cloud Droplet Effective Radius	Ice Crystal Particle Size	Polarimeter VIS-SWIR spectrometer	Cloudbow observations, High spatial resolution bispectral retrievals
Cloud Droplet Concentration			
Cloud Areal Fraction		VIS-SWIR spectrometer	High spatial resolution to resolve broken cloud
Cloud Albedo			
SW Cloud Radiative Effect		UV-SWIR spectrometer	High spatial resolution
Precipitation rate		Improved W-band	Near surface detection
	Cloud Top Vertical Velocity	Tandem Stereo Cameras	Cloud-scale vertical motion
	Cloud Top Horizontal Velocity	Tandem Stereo Cameras	Horizontal motion field, PBL entrainment

4.8.3 Context

The processes which determine the cloud response to aerosol perturbations evolve on multiple timescales. Thus, the geostationary PoR will provide useful diurnal context to the asynoptic observations from ACCP. Studies coupling long-term suites of ground-based observations with high resolution modeling (Gustafson et al. 2020) will provide complementary insights into aerosol impacts on clouds versus the diurnal evolution of clouds. Objective 8 will also benefit from the emerging capabilities of large-domain high resolution modeling, which allow direct simulation of dynamical and thermodynamical processes which must currently be parameterized in global models. Recent experiments with turbulence-resolving models embedded within coarser global models (Terai et al. 2020) represent the sort of evolving model advances that will improve our ability to model aerosol-cloud interactions over the next decade.

4.8.4 Key advances

ACCP will advance science with a suite of observations providing improved accuracy and new variables to improve process understanding. ACCP will provide improved observational capabilities in several key areas: improved radar capabilities to detect and resolve the profile of precipitation within the marine boundary layer; improved aerosol retrievals from HSRL and joint polarimeter-HSRL observations; observation of cloud-level dynamics and cloud vertical motion from the tandem stereo cameras; and improved retrievals of cloud properties.

Table 8.1 summarizes key advances expected from selected ACCP variables. These include retrievals of aerosol absorption from joint lidar-polarimeter-HSRL observations and accurate aerosol extinction profiles within the PBL from HSRL, which provide a measure of aerosol loading near cloud base and a vertically resolved proxy for aerosol size. Biases in cloud property retrievals from the current observing system will be reduced due to the sub-km spatial resolution of the ACCP spectrometer. Polarimetry will provide accurate cloud-top droplet size measurements using cloudbow observations. Observations of vertical and horizontal cloud-top motions from the tandem stereo cameras will provide unique information on the dynamics of shallow clouds and the PBL.

5. ACCP Applications Goals and Objectives

ACCP explores the fundamental questions of how interconnections between aerosols, clouds and precipitation impact our weather and climate, addressing real-world challenges to benefit society. The ACCP Applications Impact Team (AIT) is charged with ensuring that applications are considered to the greatest extent possible in mission design. Specifically, the goals and objectives of the Applications effort are to:

- Define the key applications criteria to be considered in the mission concept
- Identify applications and their readiness levels early in the mission lifecycle
- Assess the feasibility of integrating end-user needs in mission development
- Engage users and solicit feedback to integrate user needs in the mission design concept
- Characterize Communities of Practice and Potential within a Community Assessment and Report (CAR)

During the ACCP study phase, the AIT summarized knowledge from user communities across a diverse range of NASA and partner missions, NASA Applied Sciences programs and mission Early Adopter programs. The goals of this engagement were to identify what PoR satellites, instruments and products are being routinely used by stakeholders in federal agencies, state organizations, NGOs, private and public companies and the thematic areas they represent. In addition to internal expertise, the AIT has reached out to a range of communities and stakeholders, including research organizations, operational modeling and forecasting centers to better capture user needs, opportunities and ways to connect to ACCP throughout the mission development. This has included 2 ACCP Applications workshops with one planned, engagement during scientific conferences, over 60 interviews, and information solicited through trainings and surveys.

Through these engagements, the AIT has identified 75 potential enabled applications that are summarized in our Applications Traceability Matrix. These are further divided into five thematic areas shown below. For scoring purposes, 12 enabled application areas were selected to take full advantage of ACCP measurements and would have a high and immediate impact in the community.

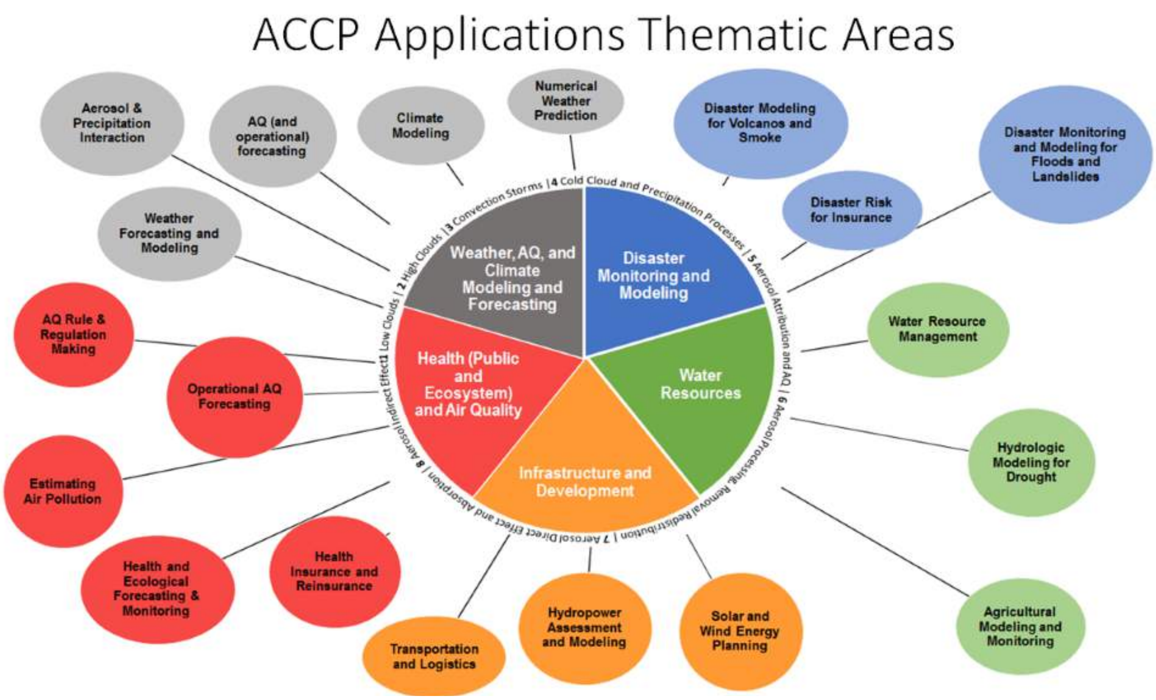


Figure 5-1. Key applications thematic areas and enabled applications identified as relevant to the ACCP study. These applications are further defined in the Applications Traceability Matrix.

In the sections below, several of the key enabled application areas are outlined. The goal of these sections is to provide an overview of community needs and current applications, as well as how ACCP may contribute to and enhance decision making to provide meaningful impacts to society. The overarching goal of the applications effort is to improve the capacity for transitioning science to applications to make it possible to more quickly and effectively achieve the societal benefits of scientific exploration, and to generate applications more responsive to evolving societal needs. This work seeks to maximize ACCP's benefit to impact decisions through early engagement in the mission development phase, including early adopter programs, development of synthetic data, connecting stakeholders with current mission data, and airborne and suborbital programs to prepare them to apply observations as soon as ACCP mission data becomes available.

5.1 Disaster Monitoring and Modeling

Severe Weather and weather-related disasters cause hundreds of deaths, thousands of injuries and cost billions of dollars each year in the U.S. alone. NOAA's National Center for Environmental Information estimates that in 2020 alone we experienced 22 separate billion-dollar weather and climate disasters, far surpassing the 16 events in 2011 and 2017, with combined $95 billion in damages (https://www.climate.gov/news-features/blogs/beyond-data/2020-us-billion-dollar-weather-and-climate-disasters-historical). The FAA estimates that about 68% of commercial air travel delays are due to inclement weather. Likewise, unfavorable weather is the cause of about 85% of all crop losses in the U.S. Phenomena like hurricanes, wildfires, hailstorms, tornadoes, derechos, floods, blizzards, and droughts impact vast segments of the population even when they are not in the direct path of these weather events.

As the climate changes, it is imperative that resilience and adaptation are improved by understanding what environments are likely to produce severe weather, what is the timing and longevity of storms, and how storm development and intensity are impacted throughout the day and by other environmental factors, like the presence of certain aerosols. By enhancing our understanding of these phenomena, improvements in prediction and preparedness can be made that will ultimately reduce their impacts.

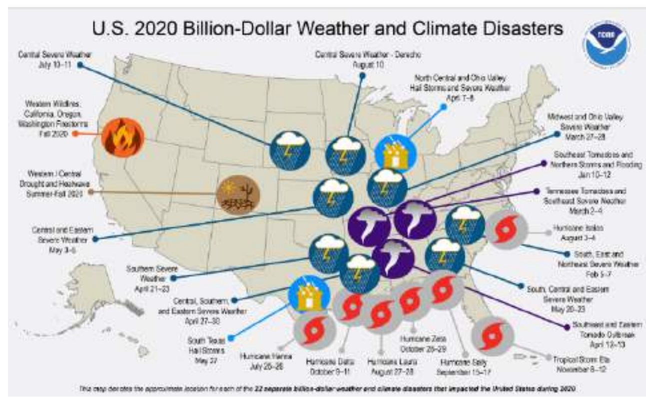


Figure 5.2. In 2020, the US experienced 22 billion-dollar weather and climate disasters, far surpassing the 16 in 2011 and 2017. ACCP will advance severe storm forecasting by observing vertical air motions in storms and atmospheric parameters relevant for weather forecasting. Figure from https://www.climate.gov/news-features/blogs/beyond-data/2020-us-billion-dollar-weather-and-climate-disasters-historical.

The ACCP mission will facilitate these advances by providing revolutionary new satellite observations of cloud and precipitation processes responsible for these severe weather events, by providing novel observations and enhancing existing datasets in weather forecast models and for weather monitoring that will support a variety of communities, such as logistics, aviation, and agriculture. Such observations will help answer key questions posed by the 2017 Decadal Survey: "Why do convective storms, heavy precipitation, and clouds occur exactly when and where they do?"

5.1.1 Improve Timing and Location of Severe Weather

Predicting the timing and location of severe weather impacts a number of industries. In the transportation sector, air traffic rerouting is particularly costly; especially in traditionally data-deprived regions, like trans-oceanic flights where airlines are often left responding to inclement weather rather than planning for predicted events. Likewise, supply chain managers must plan for changes in routes and demand in response to severe weather or weather disasters. Emergency managers, including those at the municipal level all the way to FEMA, need to be able to coordinate responses and move resources to appropriate communities that are impacted by catastrophic weather, which is time-consuming in situations where every second counts. The new information and model improvements facilitated by ACCP will help prepare the transportation sector in advance of severe weather, allowing these industries and agencies to move people, goods, and equipment more efficiently and safely.

5.1.2 Improve Understanding and Modeling of High Impact Events

Observations from ACCP also help improve our understanding and modeling of high impact events, such as hurricanes and tropical cyclones. Many scientists are currently researching how the changes of a tropical cyclone's size and vertical development throughout the day (called a diurnal cycle) can be related to changes in its intensity in the future. ACCP will provide additional observations of tropical cyclones at different times of day that will further advance the understanding of the evolution of these phenomena and be monitored in a timely manner by forecasters, such as those at the National Hurricane Center, to inform their assessment of changes in tropical cyclone structure and intensity and convey a more robust prediction of the impact to stakeholders. This results in advanced and more accurate warning of rapidly intensifying storms, helping communities prepare for evacuations and storm mitigation procedures earlier and safer.

The novel observations provided by ACCP will enhance our understanding of storms associated with severe weather events and improve our predictive capabilities of phenomena such as hurricanes, hailstorms, tornadoes, and derechos. Beyond the lifespan of the mission, the new scientific understanding facilitated by ACCP will be carried forward into forecasting and monitoring weather events and ultimately improve our preparedness for and resiliency to severe weather.

5.1.3 Improve Model Parameterizations

ACCP will help improve our understanding of severe weather around the globe by providing unprecedented observations of processes that govern storm intensity, such as novel measurements of vertical motions within clouds and the interaction between aerosols, cloud ice, and liquid water in clouds. These observations will be used to improve the models, beginning with a more accurate depiction of the atmosphere, and by facilitating a more informative validation of model forecasts. More importantly, the ACCP observations will help improve the model parameterizations and assumptions, in an effort to improve the model's skill in forecasting severe weather. These global observations can be utilized by modeling communities here in the U.S. as well as our partners throughout the world, like the European Centre for Medium-range Weather Forecasts, which contributes to our overall body of knowledge and benefits the U.S. and international weather forecasting communities.

5.1.4 Impacts of Wildfires and Smoke

Extreme wildland fires have continued to compel alarming headline news over the last decades, each year setting new records somewhere on Earth. In 2020, records were broken in California, yet again, and record-setting fires burned across the planet in Australia and Siberia. Under current climate projections, extreme wildland fire events will continue to devastate communities. Smoke from fire directly emits particulate matter (PM) and results in increases in ozone, both of which are pollutants the Environmental Protection Agency (EPA) regulates as hazardous air pollutants. Smoke statistically increases hospital visits that are directly associated with increases in respiratory and cardiovascular symptoms and deaths. The annual economic estimate of short-term smoke exposure is between $11-20B, with a long-term estimate between $76-130B, which surpasses firefighting cost (Fann et al., 2019).

Figure 5.3. True-color image captured by the MODIS instrument on NASA's Terra satellite at 12:15pm local time on August 17th of the August Complex Fire in Northern California. Timely data on the location of smoke from wildland, agricultural, and prescription fire smoke is vital for monitoring groups such as the U.S. Forest Service and Environmental Protection Agency. From https://www.nasa.gov/feature/goddard/2020/nasa-observations-aid-efforts-to-track-california-s-wildfire-smoke-from-space

ACCP will raise the bar for science and applications by providing timely data products with unprecedented accuracy of wildland, agricultural, and prescription fire smoke. Currently, we are limited by aerosol uncertainty, and lidar data are not available in near-real time. Numerous stakeholder communities will benefit from the host of instruments onboard ACCP that will provide unparalleled and timely information on the vertical extent (Figure 2) of critical aerosol sub-types (e.g., smoke, urban, marine).

5.2 Health and Air Quality

Outdoor air pollution is estimated to cause over 4 million premature deaths annually around the world (WHO, 2018), with most being attributed to $PM_{2.5}$ and costs more than $5 trillion in lost labor income and welfare losses annually (World Bank 2016). People living in Low-and-Middle Income Countries (LMICs) are disproportionately (91%) burdened with the mortality associated with outdoor air pollution (WHO 2018) and the annual number of deaths are projected to more than double by 2060 (OECD 2016). de Sherbinin et al. (2014) noted that most of the world's population have little or no information on the health risks of air pollution.

In the U.S., roughly $65 billion is spent annually on mitigating air pollution, resulting in $2 trillion in benefits, including over 160,000 cases of reduced infant and adult premature mortality (US EPA 2011). By 2060, 6 to 9 million premature deaths worldwide are expected as a result of poor AQ, with the associated annual global welfare costs projected to rise from U.S. $3 trillion in 2015 to U.S. $18 to $25 trillion in 2060 (OECD 2016).

The impact of the particles we breathe in depends on the size and composition (type) of particle. Black carbon, organic carbon and dust can cause illness (morbidity) and mortality while there are no reported health effects from inorganic particles such as sulfates, and sea salt, or large particles that do not penetrate deep into the respiratory cavity. Therefore, to answer the 2017 Decadal Survey Question W.5 – "*What processes determine the spatio-temporal structure of important air pollutants and their concomitant adverse impact on human health, agriculture, and ecosystems*?", the aerosol size and composition must be known. The ACCP lidar will answer this question more effectively than the POR which cannot unambiguously determine aerosol type and size. The ACCP mission will also continue lidar measurements as the NASA CALIPSO satellite is not expected to operate beyond September 2023 at the latest.

ACCP will provide unprecedented observations of aerosol characteristics as close to the surface as possible for air quality applications. Amendments to the clean air act during the ACCP era in the 2030s are expected to call for data to support rules and regulations based on smaller particle sizes (e.g., PM_1 - concentration of Particulate Matter, PM less than 1 μm in diameter) and particle compositions (e.g., black carbon). Since the aerosol extinction profile can be highly variable even in the planetary boundary layer (PBL), the US EPA and all the States measure PM at a height of not more than 10 m above the surface to monitor and enforce the National Ambient Air Quality Standards (NAAQS). Observations that do not quantify accurate extinction in the PBL, such as those from passive measurements are extremely uncertain for air quality and health applications. This is the main reason air quality practitioners from the local to the federal level have been slow to adapt satellite measurements for air quality forecasts, planning, and management. The ACCP instruments will afford the applications community a significant advancement over the PoR, including retrievals of PM_1, and $PM_{2.5}$ near the surface for the first time from space-based lidars. The extinction measurements from the lidars are converted to PM concentrations using a mass extinction efficiency (MEE). MEE can range over one order of magnitude from ~ 1 (Dust, dust-like) to ~ 10 (black carbon, elemental carbon) g m^{-2}. The MEE depends on **the type of aerosol**. Since ACCP HSRL retrieves aerosol type at higher fidelity than the PoR, ACCP estimates of $PM_{2.5}$ will be significantly superior to the PoR estimates.

5.2.1 Air Quality smoke forecasts

Air quality smoke forecasts will include accurate and timely smoke information, so the public can take action to protect their health. Smoke is a hazardous pollutant at the surface near fires, but through injection and transport at higher altitudes, smoke can negatively impact downwind communities far from the fire source. Thus, accuracy of smoke transport in models depends on knowledge of the vertical extent of the smoke layers. This information is crucial to estimate the impact of smoke on public health near and downwind of smoke sources. While battling fires, the firefighting community substantially benefit from intelligence on the vertical distribution and horizontal of smoke (e.g., helicopter and ground transport safety). This information is also used for air quality smoke forecasts, and community health.

Figure 5.4. A view of San Francisco skyline in September 2020 when wildfires across the region reached 2.2 million acres and cut off power to hundreds of thousands of residents. 38 million people in the Western US were exposed to unhealthy levels of air pollution from wildfires in 2020. Photo Credit**:** Jessica Christian/San Francisco Chronicle/Getty Images.

5.2.2 Smoke modeling communities

Smoke modeling communities will be substantially advanced by the host of information provided by ACCP that can be used to enhance the parameterization of models as well as verify and validate modeled smoke transport. In normal fire years, small fires in the southeastern U.S. burn as much area as in the western U.S., but because these fires burn at times when no satellites are overhead, these fires are poorly quantified. ACCP will provide the ability to make diurnal observations of smoke that adversely affects the air quality and health of people in these populated underserved regions.

5.2.3 Rules and regulations

Authorities require certainty to set and monitor rules and regulations of criteria pollutants. ACCP will provide unprecedented accuracy on the smoke aerosol characteristics including size and type information required by these organizations. Diurnal information will help quantify emissions and transport for modeling and decision support tools used by the EPA and states.

5.2.4 Health models

Aerosol type information provided by ACCP are particularly suitable for health modeling and trend studies. Accurate estimates of smoke aerosols were previously not available, so the relationship between antecedent aerosols and long-term health has not been explored in the statistically significant sample needed to advance health models. This information is vital, and particularly critical in remote and underserved regions of the US and world. The knowledge gained from the accurate representation of smoke chemical and microphysical characteristics in health and air quality models will result in long-term effects on public health policy well beyond the lifetime of ACCP.

5.3 Weather, Climate, ad Air Quality Modeling and Forecasting

Societal and environmental impacts from accelerated changes in Earth's climate have become increasingly visible across the United States, with different regional effects ranging from extreme heat and drought, increased wildfires, sea level rise, and more intense precipitation and flooding. The costs of climate change are projected to range in the hundreds of billions of U.S. dollars across the most impacted regions by the end of this century. However, state-of-the-art climate models are fraught with uncertainties, including model parameter settings, parameterization schemes, and representation of model physics (e.g., cloud feedback), which lead to a wide range of climate outcomes for this century. These uncertainties strongly impact the accuracy of forecasts in the shorter time scales, ranging from subseasonal-to-seasonal (S2S) and interannual, affecting our ability to plan for the adverse effects from extreme events and atmosphere-ocean cycles that have global reach and affect long-term forecasts.

5.3.1 Seasonal to Subseasonal Forecasting

Communities spanning the humanitarian, public heath, energy, water, and agricultural sectors could benefit from more accurate climate and S2S forecasts. For the agricultural sector, improved forecasts would enable better crop management, irrigation and fertilizer planning, and product marketing strategies. As for water resource management, this sector would greatly benefit from more accurate forecasting on a variety of time scales. In particular, the Western U.S. experiences prolonged periods of droughts that alternate with periods of extreme precipitation – from the mega-droughts to flooding caused by Atmospheric Rivers. The alternation of these conditions is affected by atmosphere-ocean cycles that drive El Nino/La Nina events that are not well predicted by our climate models. Even forecasts on a shorter time scale are still not accurate enough to determine where an Atmospheric River event will hit land, how long it will last, the expected precipitation, and associated flooding. As the Co-Chair of the western states water council, Jeanine Jones, pointed, there is a need of guidance on water management on a variety of temporal scales: from forecast-informed reservoir operations to prevent dams' failures during an Atmospheric River event, to information on the beginning and duration of the wet season, to seasonal snowpack forecasting to provide critical information to decision makers regarding water management. All this has then applications to agriculture management and developing increased readiness for fire protection during periods of prolonged drought.

The Eastern U.S. are equally in need of improved S2S prediction of the character of the upcoming hurricane season to make informed decisions on disaster management. On the climate scale, accurate forecasting of the hurricane activity in the next decade has significant implications for the development of plans for mitigation of hurricane-related damages. Such efforts include developing long-term strategy for the operation of the electrical grid, building levies to protect vulnerable regions from storm surges, designing new urban development plans to avoid building in low-laying regions that are vulnerable to flooding from torrential rains. ACCP will provide a revolutionary suite of observations to advance climate models and, consequently, support decision-making and societal challenges related to climate change in the decades to come.

5.3.2 Climate Modeling

Climate modeling represents a cross-cutting application theme of ACCP, as the suite of cloud, aerosol, and precipitation observations from the mission will help inform models and policy making decisions. Observable priorities in the 2017 Decadal Survey include cloud and aerosol properties, vertical profiles of cloud and aerosol properties, and coupled cloud-precipitation and dynamical state information to better understand their effects on climate, hydrological cycle processes, and cloud-climate feedback. The ACCP mission will meet these observable priorities and enhance the current PoR to enable improved climate modeling capabilities on a variety of temporal scales, including the very actionable S2S forecasts.

Uses of ACCP observations will enable a better understanding of several key Decadal Survey questions regarding improvements in the observed and modeled representation of climate variability and reducing uncertainties in cloud and aerosol feedbacks. Climate and S2S forecasts will directly benefit from ACCP observations through improved model initialization states and, most importantly, by providing critical and novel observations to help improve the model parameterizations for clouds and aerosols. Vertical profiles from the lidar will be especially valuable for better characterizing the vertical representation of aerosols in climate models and reducing uncertainties related to aerosol feedback. Higher frequency microwave channels (>200 GHz) from ACCP will provide important information on water vapor throughout the troposphere, which can feedback to clouds and precipitation in climate models and lead to more realistic forecasts. Vertical profiles of the radar-derived cloud and precipitation particles, and especially the novel Doppler observations of vertical velocity within clouds, will provide unique observations of the cloud structure and dynamics to help constrain the models and improve their realism. The high-resolution observations from ACCP should be particularly suited for complementing future climate models as grid spacing continues to increase. Altogether, the unprecedented observations from the ACCP mission will benefit end users and stakeholders in the climate modeling community, including NOAA, NASA, ECMWF, IPCC, and the United Nations.

5.3.3 Air quality modeling

In regions where there are no ground measurements of PM, the EPA and thus the public has no indication of the extent of air pollution, a situation that has deleterious public health implications. ACCP measurements of extinction will be used to estimate PM in some areas and in others, will provide profiles of aerosol extinction and type to constrain air quality model output and to improve their accuracy. The EPA produces a daily air quality index (AQI) which includes particulate matter concentrations. The latest surveys show 75 -80% of the public are aware of AQI and 50% report taking action based on the AQI.

The accuracy of the daily (and forecast) AQI and forecasts produced by NOAA's National Air Quality Forecasting Capability depend on the spatial resolution, latency and accuracy of satellite-observed AOD, and the validity of the relationship between column AOD and surface PM. The vertical profiles of extinction provided by ACCP will improve the accuracy of these estimates. The combination of lidar and polarimetry on a single platform will allow observations of aerosol properties at vertical and horizontal resolutions never before available to the modeling communities.

5.4 Water Resources

Growing human population, increased demand for water and energy, and a changing climate have contributed to concerns of how freshwater resources, food supply and production may be stressed. Both water resource managers and the agricultural community need to know the amount, distribution, timing and onset of seasonal rain and snow to prepare for freshwater shortages and forecast crop yields. Remotely sensed precipitation estimates play a key role in predicting changes in freshwater supply and agricultural yields. Remotely sensed gridded precipitation estimates play a key role in predicting changes in freshwater supply and agricultural forecasting. ACCP will contribute to the PoR to continue and advance a long record of global precipitation vital for monitoring the variability of terrestrial water that is fundamental for a wide range of stakeholders.

5.4.1 Freshwater Availability

Only 3% of Earth's water is freshwater, and less than 1% is available for human use. The cyclical nature of freshwater moving around our world has led to the overarching science question that NASA is trying to answer about water on our world – where it is, when it is, and in what condition. In addition, as the world warms due to climate change, NASA scientists are investigating how the world's water cycle is affected by and has effects on the Earth's climate. Quantifying the variability of extreme flood or drought conditions is vital to understanding and forecasting the availability freshwater resources worldwide. Water resource managers rely on accurate precipitation measurements to monitor freshwater resources necessary for human activities including public consumption, irrigation, sanitation, mining, livestock and powering industries. Gridded precipitation and other information are pulled into portals networks such as the World Resources Institute Aquaduct "Water Risk Atlas" (https://www.wri.org/aqueduct), which is used by stakeholders around the world to characterize water supply and risks in different regions. Leveraging both the PoR and new observations from ACCP, we will be able to continue the critical record of precipitation variability globally, which is important to a wide range of diverse stakeholder communities.

5.4.2 Agricultural Forecasting and Food Security

Remotely sensed precipitation estimates play a key role in monitoring and modeling efforts for organizations and companies that track food and water security. In addition to the amount and distribution of seasonal rainfall, the timing of the onset of rainfall is an important variable for early estimation of growing season outcomes like crop yield. With the global coverage of current PoR satellites such as GPM, and the potential data provided by ACCP can provide key information within agricultural forecast models to analyze and predict crop yield. These communities primarily make use of gridded precipitation products to inform potential yield estimates and highlight where there may be surpluses and deficits. Remotely sensed rainfall is a critical part of hydroclimate monitoring for organizations that track food and water security, like the Famine Early Warning Systems Network (FEWS NET; www.fews.net), particularly in areas where there is limited in situ rainfall gauge information. Knowledge of both the amount and distribution of rainfall as well as the timing and onset of precipitation during the growing season are important metrics that can significantly influence estimation of growing season outcomes like crop yield loss.

5.5 Infrastructure and Development

The impacts that society faces to extreme weather and climate impacts largely translates to vulnerabilities or damage to infrastructure and can have deleterious effects on development. Information on precipitation, aerosols, and clouds is already routinely used within different communities to support energy forecasting, characterize of potential yields at hydropower facilities, and inform transportation and logistics services. This is also an area of potential exploration as the communities continue to innovate and make greater use of Earth observations, including those coming from ACCP.

Figure 5.5. Climate and weather are significant factors affecting agriculture production around the world. The correlation between crop volumes and weather can result in a successful yield or a financial disaster. Accurate estimates of extreme precipitation can help farmers and agricultural insurance providers to better mitigate damage or protect against losses. **Credit:** USDA photo by Bob Nichols.

5.5.1 Transportation and Logistics

Hazardous weather such as extreme precipitation, fog, and severe storm systems are known problems for the transportation and logistical sectors, often leading to poor visibility, turbulence and airplane icing issues and flash flood events. Consequently, these conditions may influence disruptions in transportation operations and impact safety, leading to severe economic damage. Given these issues, identifying data needs and priorities to improve weather monitoring and forecasting for these sectors are important and could have significant benefits for society.

Continued incorporation of Earth Observation data will be an opportunity for logistics companies to monitor and anticipate impacts to their facilities and supply chain partners. ACCP data, through value added service providers, may ultimately improve accurate predictions of precipitation that may impact supplier and customer access, disruptive air quality events, and seasonal weather that could affect supplier availability and pricing. ACCP could engage this community through targeted training events to help crisis managers understand the value of these data products, but adoption will happen through service providers. Two value-adding use cases for ACCP data are outlined below: allocating resources to maintain business continuity and identifying disruptions in supply chain.

5.5.2 Aviation

Aviation weather services are provided primarily by the federal and private sectors, including the FAA, NOAA, National Weather Service, and operational airline companies. Accurate and timely reports of weather conditions are provided through web portals and are needed to feed information to end users such as air traffic control centers, airport towers, flight dispatch, and pilots in the form of high-resolution gridded precipitation and lightning products for aviation safety and efficiency.

An understanding of aviation impact variables such as ceiling, visibility, turbulence, and icing and the ability to produce short-term forecasts at local and regional scales are particularly important for flight operations. The incorporation of EOS data into aviation weather services has been well underway. Examples include GOES-16 imagery to detect icing threat areas, convective storms and fog; GOES-16 Geostationary Lightning Mapper (GLM) to characterize convection and icing probability; and IR imagery from Meteosat-9 to identify deep tropical convection.

There are some unique and specific challenges and needs for using EOS data for operations in the aviation industry. Ingestion of small ice crystals into jet engines and aircraft ice accumulation (e.g., icing) are well-known aviation hazards. To detect these threats, accurate detection and distinction between freezing rain and freezing drizzle as well as monitoring of high ice water content (HWIC) at near-surface and cruise altitudes are needed. However, end users have reported that precipitation types and HWIC are not easily detectable by traditional ground-based radar or geostationary satellites used within most operational systems. Measurements of fog layer depth and extent are particularly needed at all hours and at a higher resolution (e.g., airport level) for improving visibility forecasts. In terms of monitoring convection that can cause severe storm systems and hazards such as turbulence, aviation end users expressed their challenge in obtaining vertical profile information in data sparse regions as well as hourly information of cloud bases and more accurate total and frequent lightning measurements. End users also expressed a need for more coverage at higher latitudes and at higher resolutions to capture changes at local airports. Lastly, aviation-based personnel conveyed their frustrations at the slow pace of moving research to operations in the aviation community. They described that implementing new products and technology takes time, approximately 7-8 years, which can influence operations, and needs to be considered with new EO technological developments.

Figure 5.6. Improved awareness of environmental variables such as ceiling, visibility, turbulence, and icing and enhances the ability to produce short-term forecasts at local and regional scales that are particularly important for flight operations. Cory W. Watts [CC BY-SA 2.0], via Wikimedia Commons.

With the current NASA program of record and future observables related to the ACCP study, aviation end users have expressed specific needs and future opportunities to support and enhance applications. These include improvement in three-dimensional measurements of storms (e.g., the ability to "see" inside the storm), modeling and understanding of convective storms to avoid turbulence, fog ceilings and low clouds to improve visibility and decreased incidences of delays, and more precision for developing forecasts for 12-14 hours before a flight. Aviation end users will continue to ingest satellite data into their systems and processes for validation and verification and are looking forward to new and innovative measurements to advance their predictions and forecasts for operations.

5.5.3 Energy

In many areas, energy infrastructure assets, such as power plants and electric grids, can suffer damage or disruption in service due to a variety of climate-related impacts like extreme precipitation, high temperatures, drought, and rising sea levels. For example, warmer temperatures and little rainfall can cause changes in peak streamflow conditions that affect hydropower generation. Heavy precipitation events and flooding can impact a region's energy infrastructure, including electric grid equipment, which has cascading effects on freshwater supplies and emergency services. The impact of aerosols such as dust may impact solar panel performance or have physical effects on the hardware itself. Changes in climate and extreme weather events affects all cycles of the electric power industry, including grid operation and planning, power generation, and power consumption (load). Understanding local precipitation and climatological patterns can improve a region's power efficiency, economy, and overall safety. Therefore, it is critically important to monitor severe weather, estimate heavy precipitation, and produce accurate climate estimates to identify, detect, and forecast the demand and supply of power for a region.

ACCP provides opportunities to explore different areas within the energy sector, providing information on aerosols, extreme precipitation, and cloud cover that can directly support key decisions or analyses within the energy sector. This includes the use of climatology data in the prediction of energy demand, development, harvesting, and production of non/renewable energy resources, and load forecasting. It also enables and supports the hydropower industry who are looking to evaluate the feasibility of hydropower development, particularly in developing regions with limited in situ hydrometeorological networks.

5.5.4 Opportunities for enabling applications

Improved capacity for transitioning science to applications will make it possible to more quickly and effectively achieve the societal benefits of scientific exploration, and to generate applications more responsive to evolving societal needs. ACCP will enable decision making that impacts people around the world, from short-term crises to long-term plans. It will advance:

- Weather Forecasting by observing vertical air motions in storms and atmospheric parameters for severe storm forecasting
- Climate Modeling through measurements that reveal the inner workings of aerosol, cloud and precipitation processes to improve climate projections
- Air Quality through more precise measurements of aerosols to better forecast impacts on human health
- Disaster monitoring by conveying observations of volcanic plumes, wildfire smoke, and extreme precipitation for rapid response

6. The ACCP Approach

6.1 Heritage

The ACCP observing system will benefit from, and in several ways make great strides beyond, the heritage from the A-Train suite of sensors that flew in a sun-synchronous orbit. While not designed as a precipitation mapping mission, ACCP will also build on heritage from TRMM and GPM in inclined orbits by providing diurnally varying observations. The extent to which ACCP provides continuity with TRMM and GPM will depend on whether the JAXA Ku Doppler radar can be accommodated as part of the final architecture.

The A-Train provided joint aerosol, cloud, and precipitation information from a collection of independent missions (CloudSat, CALIPSO, Aqua, and Terra) flying in formation. Cloud profiles were measured by a W-band cloud profiling radar on CloudSat and a 532- and 1064-nm backscatter lidar on CALIPSO, aerosol profiles were obtained from the CALIPSO lidar, cloud optical properties and aerosol optical depth were provided by the MODIS (Aqua and Terra) multi-spectral imager, and surface precipitation estimates were retrieved from the AMSR-E (Aqua) passive microwave radiometer. The formation flying of the A-Train missions ended in 2020. The EarthCare mission, a joint ESA/JAXA mission, is expected to launch in June 2022 and have a mission lifetime of no more than 5 years. EarthCare will carry a UV (355 nm) HSRL lidar, a W-band Doppler radar, a multi-spectral imager for cloud and aerosol horizontal distributions and properties, and a broadband radiometer for measuring the impacts of clouds and aerosol on atmospheric radiation on longer temporal and spatial scales. Key advances over the A-Train are the Doppler capability of the W-band radar and the HSRL capability of the UV lidar, although it will lack the 532- and 1064-nm frequencies of CALIPSO.

ACCP will take advantage of advances in SmallSat sensor technologies for several of its instruments to provide capabilities beyond the A-Train and EarthCare in a single mission. The ACCP instruments included in the final three recommended architectures are shown in Table 6-1. For the dual-orbit solution (Architecture D1A, see section 9), the polar-orbiting component of ACCP is expected to make significant advances on the capabilities of the A-Train and EarthCare. The radar will use both W- and Ka-band frequencies, both with Doppler capability, to profile clouds and precipitation to within a few hundred meters of the surface and provide passive capabilities for joint active-passive retrievals. The radar uses the Displaced Phased Center Antenna (DPCA) approach that significantly reduces noise in the Doppler signal and the effects of non-uniform beam filling compared to EarthCare. The radar will be paired with a passive microwave radiometer, including sub-millimeter channels, for characterizing cloud ice properties and, to some extent, measuring precipitation. The lidar provides the CALIPSO frequencies, with HSRL capability at 532 nm and significantly improved signal to noise performance and vertical resolution. The HSRL capability will allow for direct determination of the molecular and particulate extinction, enabling improved retrievals of aerosol types and properties. The lidar will be paired with a multi-angle, multi-frequency polarimeter, which will provide strong constraints on retrieval of aerosol properties during daytime and cloud and aerosol property information across a wide swath. The cloud, precipitation, and aerosol measurements are also coupled with pixel-scale estimates of the surface and top-of-the-atmosphere radiative fluxes for assessing radiative forcing associated with aerosols and clouds.

The inclined-orbit sensor suite of Architecture D1A consists of a W- and Ku-band radar, with DPCA Doppler capability at Ku, and joint active-passive measurements. The Ku frequency allows for better penetration of strong convective storms and heavy precipitation. The radar would be complemented by the same passive microwave radiometer as in the polar orbit. The Ku radar will provide limited continuity with TRMM and GPM at nadir; more complete continuity with these missions would be enabled by inclusion of the JAXA Ku radar with wide swath measurements. A key advancement relative to TRMM and GPM would be the addition of the two-channel (532, 1064 nm) backscatter lidar and a multi-angle, multi-frequency polarimeter for coincident cloud and aerosol retrievals. The lidar would provide some continuity with CATS lidar measurements from the ISS (2015-2017) to provide enhanced characterization of the diurnal cycle of aerosols.

The heritage of the ACCP sensors is indicated in Table 6.1. The radars, lidars, polarimeters, and shortwave spectrometer have heritage in both airborne and spaceborne sensors while the other sensors generally have heritage with either airborne sensors (longwave spectrometer and aerosol and moisture limb imagers) or spaceborne sensors (passive microwave radiometers, stereo cameras). The heritage of ACCP sensors to past missions and airborne instruments also means that there is a rich heritage of algorithms to support ACCP data processing for individual sensors as well as combinations of sensors.

Table 6.1. ACCP instruments are derived from technologies of Technical Readiness Level (TRL) 4 or greater. Related sets of instruments are shown here along with their airborne or spaceborne heritage.

ACCP Instrument	Airborne Heritage	Space Heritage
U.S. Radars	AirSWOT, Airborne Precip. Radar (APR)	CloudSat, RainCube
JAXA Radar		TRMM PR, GPM DPR
HSRL Lidars	Airborne HSRL	CALIOP
Backscatter Lidar	CPL	CATS
U.S. Passive Micro. Radiometer	CoSMIR	TWICE (IIP)
CNES Passive Micro. Radiometer		Megha-Tropiques SAPHIR, METOP-SG (MWS, MWI, ICI)
Polarimeters	AirHARP	HARP, HARP2
Shortwave Spectrometer	High-altitude balloon flights	CLAREO Pathfinder on ISS (2024)
Longwave Spectrometer	Airborne flights	
Tandem stereo cameras		Star trackers, LEO/GEO cameras, MISR technique
Aerosol Limb Imager	High-altitude balloon flights	
Moisture Limb Imager	High-altitude balloon, ER2 flights	

6.2 Relation to and Usage of the Program of Record

The PoR, and reliable funding to ensure its implementation, are important to Earth system science and applications that rely on long-term sustained observations of many key components of the Earth system. Given this recognition, the existing U.S. and international PoR (Table 6.2) formed an important foundation upon which the DS designated observables, including ACCP, were defined. This PoR includes NASA, NOAA, and USGS missions as well as internationally coordinated networks of operational satellites. Two such networks are the meteorological satellites coordinated by the Coordination Group for Meteorological Satellites (CGMS) and the more recent Sentinel satellites of the European Union's Copernicus Program, which together will provide continuity for a broad range of critical Earth observations.

There are several ways ACCP builds upon the PoR. Some aspects of the precipitation data record of TRMM and GPM will continue with ACCP. The vertical cloud profile data record started with the A-Train will be also extended by EarthCARE and then sustained by ACCP. There are other ways the PoR is important to ACCP. The radiation budget measurements of CERES and Libera provide important context for the ACCP radiative fluxes, while the spectral solar measurements from operational sensors including the polarimetry of 3MI provide important cloud and aerosol context. The planned global coverage from microwave radiometers and sounders offers precipitation context for the ACCP observations and the enhanced capability of geostationary imagers, coordinated with CGMS, will be directly exploited in ACCP to provide both space and time context of clouds and aerosol (Box GEO).

Table 6.2. Geostationary (GEO) and low Earth Orbit (LEO) satellite sensors (different swath, resolution, and coverage not shown) that are likely to provide aerosol and cloud observations during the ACCP timeframe (i.e., Program of Record or PoR). The orbital PoR will provide spatial and temporal context for the advanced observations from ACCP and ACCP will provide evaluation and interpretation of the orbital PoR. Note that the orbital PoR will be augmented by essential suborbital observations (not shown).

Orbit	Sensor	Platform	Channels
GEO	**ABI**[A,C]	GOES R-U	**VIS- IR**
	AHI[A,C]	Himawari	**VIS-IR**
	AMI[A,C]	KOMPSAT 2A	**VIS-IR**
	FCI[A,C]	Meteosat MTG-11-14	**VIS-IR**
	UVNS[A]	Sentinel-4	**UV-NIR**
	GEMS[A]	KOMPSAT 2B	**UV-VIS**
	TEMPO[A]	Comm. Sat	**UV-VIS**
LEO	**VIIRS**[A,C]**, OMPS**[A]**, CrIS**[C]**, ATMS**[C]	JPSS	**VIS-IR**, **UV-VIS**, **IR, MW**
	OCI[A,C]**, HARP***[1-2A,C]**, SPEX***[1-2A,C]	PACE	**UV-SWIR, VIS-NIR**
	3MI[1-2A,C]**, METimage**[A,C]**, MWS**[C]**, IASI-NG**[C]	Metop-SG	**VIS-SWIR, VIS-TIR, MW, TIR**
	ATLID*[A,C]**, MSI**[A,C]**, CPR**[C]**,**	EarthCare	**355nm, VIS-TIR, 94Ghz**
	MAIA[1-2]*****[A]	OTB	**UV-SWIR**
	MSI[A,C]	Sentinel-2	**VIS-SWIR**
	SLSTR[1A,C]**, OLCI**[A,C]	Sentinel-3	**VIS-NIR**, **VIS-NIR**
	UVNS[A,C]	Sentinel-5	**UV-SWIR**
	EMIT[A]	ISS	**VIS-SWIR**
	SBG[A]	TBD	**VIS-SWIR, IR**

*Unlikely operational > 2025
Sensor Type:
Lidar (e.g., CALIOP); **Multispectral Radiometer (e.g., MODIS)**; **Spectrometer (e.g., OMI)**; **Multi-angle Radiometer[1]/ Polarimeter[2] (e.g., POLDER)**

6.3 Suborbital Science

The ACCP Sub-Orbital Vision: The SO framework, augmented by community modeling activities, should provide a bridging framework that enables a self-consistent and seamless view of aerosol, cloud and precipitation related processes across the full spectrum of scales and measurement approaches provided by SO and ACCP orbital architectures.

Introduction: Goal and objectives

The overarching goal of the ACCP Sub-Orbital (SO) Program is to provide SO observations (surface-airborne) as an integral element of the ACCP observing system toward addressing SATM science objectives. The SO component of ACCP is necessary because a complete ACCP science approach requires data accuracy, process access and sampling resolution at fine spatial and temporal scales, in situ observation, and a process temporal and spatial evolution view that LEO satellites simply cannot provide. Implementation of a SO component to ACCP will enable more rapid and strategically targeted science to be accomplished toward satisfying SATM science objectives, concomitant with development and implementation of the ACCP orbital component. As such, SO objectives are targeted to maximizing science return and include the development of a framework in-sync with ACCP orbital architecture planning. Specific objectives include:

a. Definition of a complementary and/or gap-filling set of targeted sub-orbital science foci supporting SATM science objectives
b. Provide In situ data needed for satellite retrievals
c. Provide Calibration / Validation needs and approach(es)
d. Provide opportunities/partnerships to bridge gaps in the ACCP launch schedule and/or POR sampling.

Science Modules

Toward accomplishing SO Science objectives, the SO Working Group (SOWG) implemented a process to identify targeted science modules, potential a priori data collections and synergies with cal/val via the execution of the first of two community workshops in March 2020 (Fig. 6-3.1)

The first workshop provided an extensive set of potential science foci and a priori geophysical data collections (cal/val components being intrinsic to the recommended science). The voluminous community inputs were subsequently processed by SOWG to provide a flexible set of science foci or "modules" organized along three science themes (Fig. 6.1).

As organized, the science themes/modules can be implemented in an agile fashion, evolving with and adapting to ACCP orbital architecture needs, and programmatic budgets, while at the same time maintaining high science relevance and impact to achievement of SATM science objectives. The three science themes in Fig. 6.2 target specific aspects of ACCP SATM science objectives-focused strongly on aerosol, cloud and convective processes and their respective interactions. Note that components of cold precipitation processes (e.g., snowfall) and aerosol DRE are either implicit to the modules and/or can be specifically accomplished in the developing cal/val sub-component. The systematic aerosol component will enhance the collection of intensive aerosol properties, types and profiles as a means to establish priors for and constraints on both combined

Figure 6.1. SO science foci evolved from inputs ACCP SO Community Science Workshop and subsequent prioritization of a subset of "science modules".

lidar/polarimeter retrieval algorithms and aerosol transport models. The implementation of approaches to accomplish the SO science modules within any given theme will be addressed in a second community workshop to be held in March 2021.

Implementation Approach Framework

A set of approaches to achieve SO science modules in Fig. 6.2 will be developed within the broader "vision" for the SO component of ACCP (Fig. 6.3) using a strategy based on a "five-point" implementation framework (ordered approximately by perceived cost to implement):

1. Identify and explore existing field campaign data sets (surface and airborne) and establish degree to which these data can contribute to ACCP orbital science.

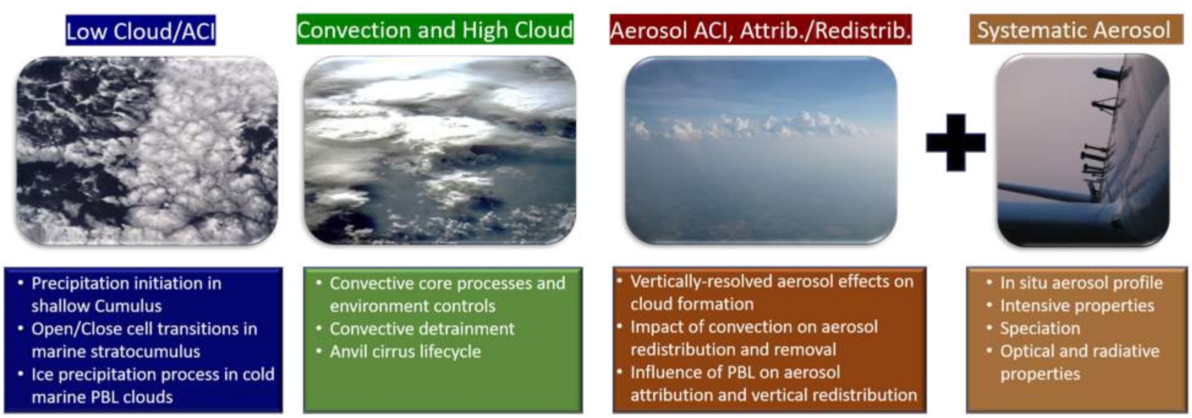


Figure 6.2. Priority ACCP SO science themes and associated modules (left), with a systematic aerosol sampling module.

2. Leverage existing global to regional datasets provided by ongoing surface (ground/ship) long-term research and/or operational measurement initiatives (i.e., DOE-ARM, EU EARLINET, ship campaigns with piggyback deployments of SOWG assets; NOAA MRMS operational radar network products and similar international efforts/data streams etc.)
3. Augment activities in (2) or like activities with ACCP-led deployment of new surface-based measurement suites using existing mobile instrumentation to supplement existing ground or sea-based supersite, or like sustained data collections or other agency/entity multi-platform deployments.
4. Directly participate and partner in larger targeted multi-platform airborne/surface-based field campaigns (i.e., EVS-like)
5. Lead major ACCP science field deployments: Multiple, single, or systematic airborne campaigns (e.g., CAMP2EX, OLYMPEX, ORACLES, TC-4, etc.).

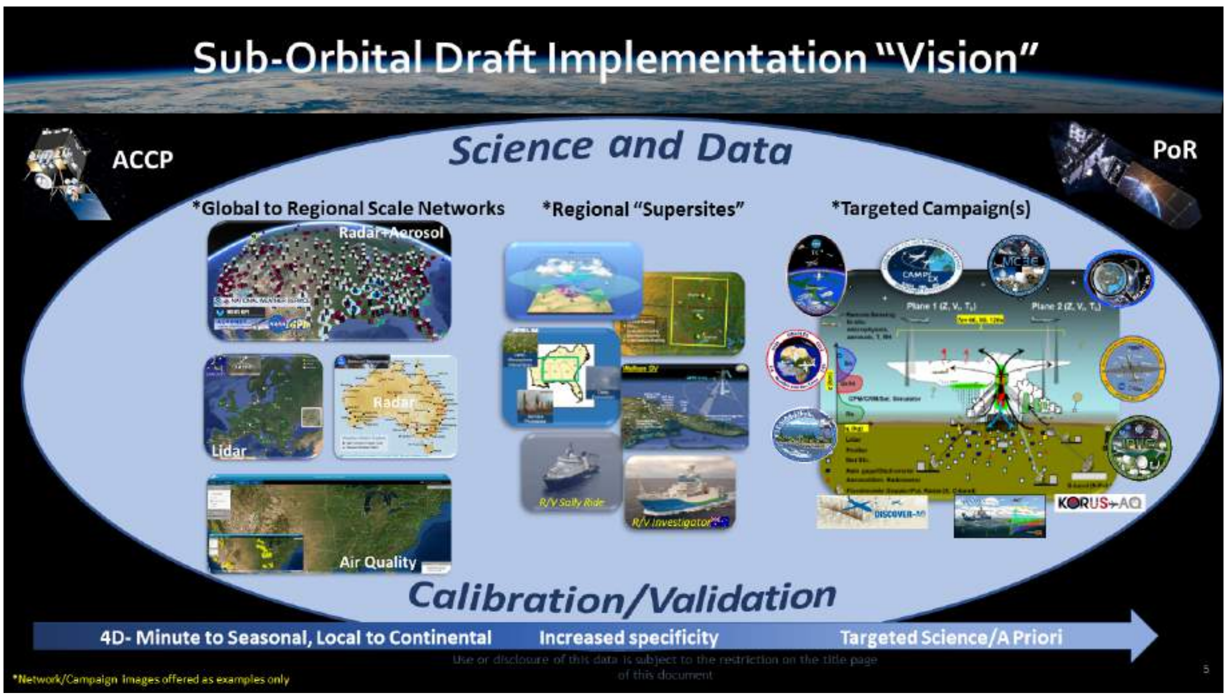


Figure 6.3. The SO implementation framework involves a hierarchy of space/time scales, existing and future associated datasets, and field campaign approaches, cal/val intrinsic to each framework sub-component.

Components of Implementation

The component vision for the SO implementation framework (Fig. 6.3) provides a hierarchical context for accomplishing SO objectives and ACCP science. The framework telescopes in scale from large global-continental to regional ground-based datasets, to targeted air, ground and/or sea-based field efforts; all of the aforementioned working within and under the aerosol and cloud observational purview of both ACCP and PoR orbital remote sensing assets. Moreover, the SO implementation strategy recognizes the existence of voluminous prior datasets at all scales of the framework that, with proper interrogation and subsequent analysis may address select sub-orbital science modules. Note here that our strategy also explicitly recognizes the "big data" aspect of the problem, necessitating modern approaches to data science including leveraging (e.g., NASA ESDS) application of advanced concepts for archiving, mining, and analyzing data.

Specific examples of framework sub-components are indicated in Fig. 6.3. For example, at the global-continental scale, existing radar networks (e.g., U.S. WSR-88D) provide Multi-Radar Multi-Sensor 4-D datasets at 0.01° x 2-minute x 32 vertical level resolution for analysis of convective scale evolution at the minute to diurnal timescales. Similar networks exist in other regions of the globe (and are used by missions such as NASA-JAXA GPM). In the same context, globally distributed AERONET sun-photometer, MPLNET lidar, EARLINET lidar provide a means to examine aerosol column properties at a combined temporal and spatial resolution and continuity that greatly complement orbiting nadir measurements of ACCP satellite-based lidar. In turn, the combined SO radar and aerosol datasets enable upscale study of aerosol-cloud-precipitation interactions over a host of contiguous timescales, intrinsically connecting SO datasets and science to improved interpretation and development of PoR satellite-based parameter retrieval algorithms, and a multi-scale/platform "bridge" to ACCP orbital statistics at a multitude of process scales. Here note that a critical cement in the SO to orbital "bridge" involves use and integration of SO observations and analyses to verify and validate the ever-increasing complexity and resolution of model physics and physically based model parameterizations over a wide range of model types. This bridging of SO datasets and synergistic modeling activities to PoR to ACCP satellite statistics intrinsically includes an ability to accomplish integrated direct and physical validation of ACCP retrieval algorithms (including improved constraints via collection of priors related to retrieval of geophysical variables) and data products, to include assessment of their overall utility benchmarked against the SO and PoR datasets.

Cal/Val

Within the broader SO framework (Figs. 6.2, 6.3) the cal/val approach will leverage established strategies used in numerous previous missions from the EOS, A-Train, TRMM, and GPM eras. While ACCP cal/val will place its focus on validating L2 to L3 geophysical variable product types, calibration of L1 data products will also be considered. To accomplish product validation activity, the SO strategy assumes the presence of, and will employ, NASA's high altitude remote sensing and in-situ airborne components with associated instrumentation (numerous active and passive microwave, lidar, and VisIR remote sensing instrumentation components, in situ cloud and chemistry instrumentation etc.) together with several NASA-funded ground-based platform/instrument resources (e.g., GPM/Precipitation Science Program radar and associated Validation Network processing architecture, Atmospheric Chemistry/Composition instrumentation in the form of AERONET and MPLNET). Complementing NASA SO instrument and platform measurements, ACCP cal/val will extensively leverage existing national and international partnerships as part of the broader SO science framework and targeted to cal/val activities as appropriate (e.g., European EARLINET distributed lidar profiles and products, aerosol, cloud and precipitation profiling measurements provided by the Department of Energy supersites, similar measurements provided by sea-going platforms such as the Australian Bureau of Meteorology R/V Investigator, and specific international airborne and ground-based network contributions of identified ACCP international partner institutions in DLR, CNES, and the CSA etc**.** The SO framework and Cal/Val activities will also endeavor to coordinate with ESD Research & Analysis Program field measurement activities as appropriate.

6.4 Modeling and Analysis Tools

The ACCP study convened a workshop in November 2020 to understand the future of modeling aerosols, clouds, convection and precipitation, and how satellite data can contribute to that future. This workshop gathered modeling and data assimilation expertise from the world's top institutions, with the purpose of answering the following questions:

1. What will be the critical science questions for clouds and aerosols in 10 years?
2. Where will simulations of clouds and aerosols across scales of space (process models to global) and time (nowcasting to climate prediction) be in 10 years?
3. What data will be available from space? What data would provide the most benefit?
4. What are the state of the art methods for confronting models with cloud and aerosol observations, including assimilation and climatological analysis techniques?

The outcome of this workshop can be found in Gettelman et al. (2021), with only a brief summary included here.

Models of the future will be higher resolution, often with refined resolution over a region of interest, and coupled with applications from air quality and human health to hydrology and runoff. These models will be integrated across scales in space and time (from regional to global, from weather to climate) and also across applications (including NWP and air quality forecasting). They will inevitably include coupled processes for clouds and aerosols.

Future observations will be refined and expanded. ACCP satellite observations will provide targeted observations with higher quality, higher spatial resolution and more, coincident variables. But there will also be significant additional observations of different variables from a myriad of sensor networks such as geostationary satellites, swarms of small satellites, and suborbital platforms. All these observations will need to be integrated (with models) into comprehensive observing and modeling systems.

This future requires comprehensive model-data synthesis capabilities that needs to be conceived in conjunction with the space-based and suborbital components of ACCP. The boundary between observations, retrieval, model and observation simulators will likely blur in the coming years. Data will be used across space and time to better initialize forecasts and *train* modeling systems. These methods will be used to advance both models and observations for better predictive skills of weather and climate. Models and data assimilation systems infused with data from advanced observing systems will be used for operational predictions and to generate expanded hindcasts and reconstruction of the climate record. These systems will take advantage the geophysical laws expressed in models to enhance the limited variables and locations available from observations, expanding them into a consistent and multivariate representation of the state of the earth system: a *data cube*.

This new paradigm will accelerate the blurring of disciplinary boundaries and foment a new generation of interdisciplinary science in which fused data and modeling tools are an essential ingredient. To realize this vision, modeling and data assimilation need to be considered as an integral part of the ACCP observing strategy, taking it beyond the limited Level 1-3 paradigm of the EOS-era missions.

7. Measurement Approaches

The ACCP measurement approach in many respects draws from our experience gained from constellations like the A-Train. That experience demonstrated the clear added benefits in combining observations that each offer different but synergistic perspectives on the properties of clouds and aerosol. Figure 7.1 illustrates the different physical processes that characterize remote sensing measurement approaches inherent to the different the observations considered for ACCP. These methods broadly fall into two categories, passive and active, with real benefits realized when measurements of different types are combined.

Passive measurement approaches include 1) methods based on deducing the extinction of radiation between source (often the sun) and detector (Fig. 7.1a) as in the example of the ALI and SHOW limb measurements under consideration as an international contribution to ACCP, 2) methods based on emission of radiation from absorbing/emitting constituents (Fig. 7.1b) and for ACCP this provides selected properties of clouds and precipitation derived from microwave radiometry, 3) methods based on scattering of radiation from natural sources like the sun or in the case of microwave emitted microwave radiation by the atmosphere and surface. Polarimeter measurements proposed for ACCP largely exploit the angular properties of scattered sunlight and the visible/near infrared spectrometer compliments other measurements exploiting the spectral structure of this scattered light.

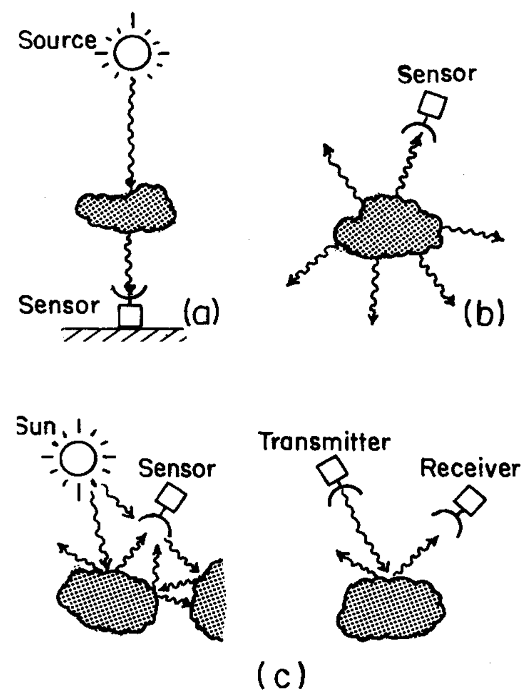


Figure 7.1 The physical processes exploited by various remote sensing measurement approaches a) extinction provides information of attenuators along the path, b) emission provides information about the emitters including their temperature and composition, c) scattering of radiation either from natural sources like sunlight used to interrogate properties of atmospheric scatterers such as aerosol and clouds or from artificial sources establishing the active methods of remote sensing that exploit echoes returned from the atmosphere and surface (Stephens, 1994).

For the most part, the passive methods provide information vertically averaged in ways that vary depending on the method. By contrast, active instruments (radar and lidar) for the most part provide unique and unambiguous profile information at explicit vertical resolutions set by the design of the instrument (e.g., the pulse length selected). When combined, the path integrated information from passive instruments offers significant benefits in constraining the profile information of the active sensors and conversely locating the scattering layers precisely with active systems advances our ability to determine cloud and aerosol properties from passive systems (add refs for examples).

The explicit profiling capability provided by radar and lidar is a basic requirement of the objectives of ACCP. Active measurement approaches, however, come with their own sources of ambiguity that can be in part managed by sensor design. Advantages of different active systems and factors that confound interpretation of echoes backscattered by the atmosphere is offered in Table 7.1 as a function of the different transmitter types. Laser light at shorter wavelengths haver the benefit of being sensitive to a wide range of particles from small sub-micron sized aerosol particles to the largest snowflakes. At the wavelengths typically adopted by lidar systems, laser light suffers significant attenuation being unable to penetrate opaque clouds of particles typical of most clouds. Interpretation of backscattered light also suffers from the backscatter-to-extinction ambiguity which makes the energy backscattered by a thick volume of absorbing aerosol indistinguishable from backscatter for a thin layer of scattering aerosol. This ambiguity is in most respects a consequence of the large variability of aerosol composition in Earth atmosphere. The HSRL ACCP lidar approach described below, for the first time, fundamentally overcomes this major ambiguity inherent to aerosol property retrieval methods.

Table 7.1. Advantages and disadvantages of laser and microwave remote sensing approaches.

Transmitter	Advantage	Disadvantage+
Laser UV, visible, SWIR wavelengths; ~0.3-1.0 X 10^{-6} m)	Sees* all particles of a few 0.1 X 10^{-6} m and greater, able to provide high spatial and vertical resolution	Attenuates heavily in moderately thick cloud, multiple scattering confuses ranging (from space)
Microwave mm wavelength (*W*-band, ~3mm)	Sensitivity* to all particles of order ~5 X 10^{-6} m and larger (most cloud particles). Minimal multiple scattering effects in most clouds.	Attenuation in moderate to heavy rainfall, multiple scattering in deeper convective clouds. Presence of small amounts of precipitation masks cloud returns
cm wavelength. *Ku*~5cm, *Ka*<1cm	Little attenuation under most rain rates. Practically no multiple scattering at *Ku*.	Lacks sensitivity to see majority of clouds and snowfall especially high latitude. Footprint increases as wavelength increases. As wavelength decreases (*Ka*), attenuation and multiple scattering effects increase

Radar backscatter (referred to as reflectivity) is sensitive to a range of larger particles, mostly hydrometeors. The shorter the wavelength (e.g., W band), the more sensitive is the reflectivity to scattering by smaller cloud drops. The sensitivity to hydrometeor scattering therefore varies with radar frequency ranging from a sensitivity to cloud drops as well as precipitation hydrometeors at W band to precipitation hydrometeors mostly at longer wavelength radars. One motivation for multi-frequency radar is to provide sensitivity across the hydrometeor spectrum.

The confounding effects of attenuation vary with frequency being most acute for shorter wavelength lidar systems, less acute for radar systems although not entirely negligible under some circumstances at W band (heavier precipitation) and at Ka band frequencies (even heavier precipitation). The effects of multiple scattering confound the profiling capability of active systems through 'pulse stretching' (Fig. 7.2) and like attenuation this varies according to frequency of transmitter, being more ubiquitous for lidar and less so for radar depending on the types of hydrometeors, their size, concentration and depth of layer (e.g., occurs more typically at W band in the strongest and deepest convection composed of large ice particles).

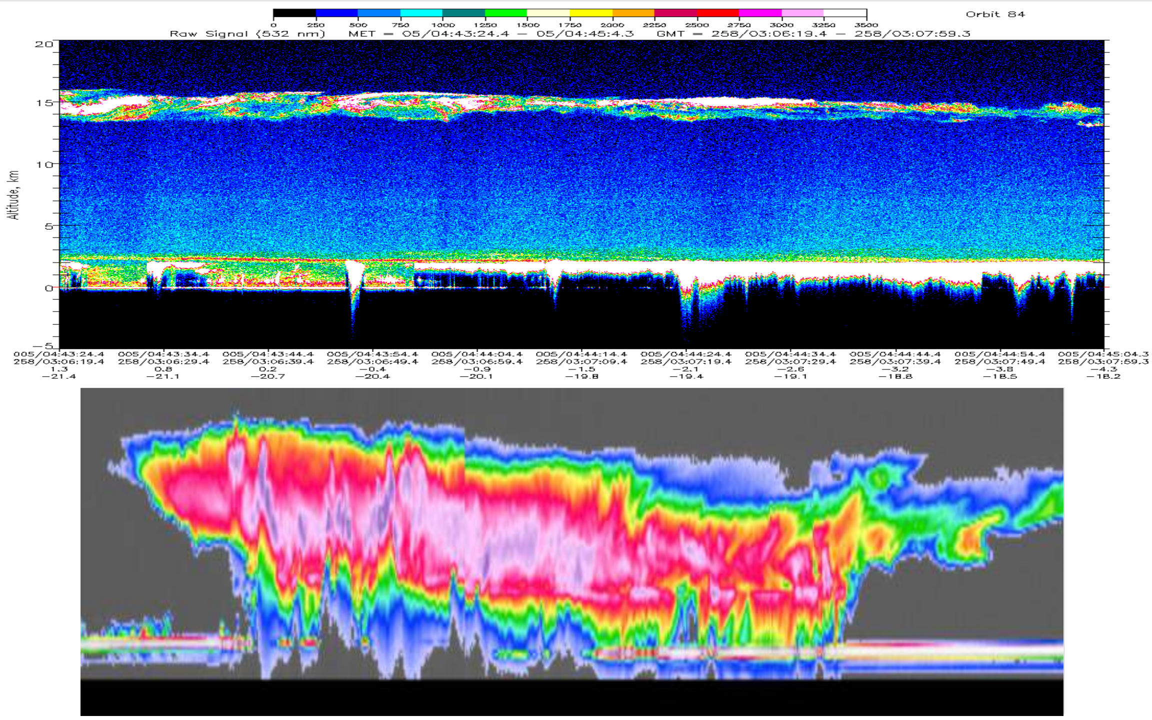


Figure 7.2 Two examples of 'pulse stretching.' The CALIPSO example (upper) illustrates how multiple scattering makes the echoes appear to originate below the surface of Earth under low clouds. The CloudSat example (lower) is from an overpass of Tropical Storm Joaquin in the Caribbean on September 29, 2015 at 1810 UTC. Multiple scattering occurs in regions where the radar is fully attenuated in the most intense parts of the convection making it appear as if the convection extends below the surface.

7.1 Radar

Different information about hydrometeors is contained in the different properties of energy backscattered by radars (and lidars). This includes the strength of backscatter itself as measured by reflectivity Z, polarization of the backscatter (such as exploited in multi-parameter radar techniques, e.g., Bringi and Chandrasekhar 2001), attenuation (e.g., Table 7.1) that if quantified also offers viable information, a (Doppler) shift in phase of the returned pulse and the spectral broadening of the backscatter which is a property explicitly exploited in the HSRL method.

The ACCP radar will provide Z, the attenuation, and the Doppler shift. In simplest terms, considering a hypothetical cloud composed of drops all of the same size, the power returned Z is proportional to the square of the water and ice content of the (radar) volume (Fig. 7.3). This proportionality is a consequence of the fact drops tend to be much smaller in size (micron to sub mm) than the wavelength of the radar transmitter (mm and cm). This intrinsic relation between water mass and reflectivity fundamentally is the reason radar is such a power tool for studying clouds and precipitation. However, for real clouds, particles in the volume range in size characterized by a size distribution. The power returned Z more realistically is only *approximately* proportional to the square of the water and ice content of the (radar) volume. The degree to which this proportionality exists varies from cloud type to cloud type and from rain type to rain type, which is why, for example, the relation between reflectivity Z and rain rate R is non-unique depending on rain microphysics. This complication also emerges at W band when drizzle forms with the scattering from these large drops completely masking cloud returns. The value of using other combinations of measurements, such as the use of radar observations at multiple frequencies, ice cloud properties derived from a combination of W-band reflectivity with lidar backscatter, combination of passive path integrated information of different types all reveal significant benefits of multi-sensor applications.

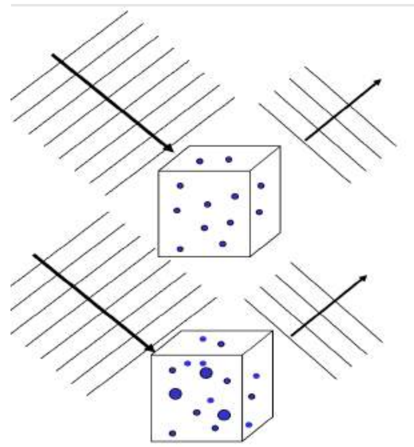


Figure 7.3 A simple schematic of reflection by hypothetical volume of scatterers. The reflectivity at radar wavelengths varies with particle size (D) approximately as D^6. When drops are all of the same size (upper), the reflectivity varies as the water content $w^2 \sim (D^3)2$. For more realistic cloudy volumes (lower) composed of hydrometers of distributed sizes, the reflectivity no longer varies in a simple and non-unique way with water content.

One the most important new capabilities of the ACCP radar measurement approach is the measurement of the Doppler phase shift of the returned echoes. The measured Doppler shift is a measure of the radial velocity of the moving scatterers. Since there are a spectrum of motions of scatters in any given radar volume, then there is also a distribution of Doppler shifts, expressed as the Doppler spectrum. The space borne radar provides a measure of the mean of this spectrum in turn providing a measure of the mean of the radial motions of the volume. These motions in principle represent the combination of the motion of air that, for example, is lifted by updrafts and the motion of drops that fall against lifted air.

The accuracy of air motion estimates from spaceborne Doppler radar is governed by three main factors (Table 7.2). The separation of particle motion from air motion ('retrieval') has an intrinsic uncertainty associated in the use of reflectivity to infer the particle component. The broadening contribution arises from a contribution from the fast moving spaceborne platform that leaks into the radar beam. A unique aspect of the technology being developed for ACCP is the displaced phase center antenna (DPCA) technique that is able to remove the platform motion to effectively achieve 0.5 m s^{-1} (or better). The third contribution arises from the effects of non-uniform beam filling (NUBF) whereby vertical motion variability within a moving footprint distorts the estimate of the mean Doppler motion of the footprint. This error systematically grows with increasing the radar footprint increases.

Table 7.2. Factors governing the accuracy of spaceborne Doppler radar.

$$\sigma_{\substack{Vertical \\ Air\ motion}} = \sqrt{\sigma^2_{retrieval} + \sigma^2_{\substack{Doppler \\ broadening}} + \sigma^2_{NUBF}}$$

	$\sigma_{retrieval}$ Error introduced by the decomposition of the observed Doppler velocity to its vertical air motion and particle sedimentation	σ_{Broad} Error introduced by the platform motion during uniform beam filing conditions	σ_{NUBF} Error introduced by the platform motion during non-uniform beam filing conditions	$\sigma_{\substack{Vertical \\ Air\ motion}}$
W band - DPCA				
Ku band non-DCPA	$\sim 1.5\ \mathrm{m}s^{-1}$	$\sim 1.5\ \mathrm{m}s^{-1}$	$\sim 1.5 - 3\ \mathrm{m}s^{-1}$	$\sim 2.6 - 3.6\ \mathrm{ms}^{-1}$
Ku band DCPA	$\sim 1.5\ \mathrm{m}s^{-1}$	$0\ \mathrm{m}s^{-1}$	$\sim 1.5\ \mathrm{m}s^{-1}$	$\sim 2.1\ \mathrm{ms}^{-1}$

7.2 Passive Microwave Radiometer

Passive microwave radiometers measure emitted energy from the Earth in the range of 1-1000 GHz. They have been used to measure surface properties such as sea ice, soil moisture, ocean salinity, surface wind speed over water, and sea surface temperature, as well as atmospheric properties such as total column water vapor, total column liquid or ice water path, precipitation, and profiles of temperature and humidity. Satellite sensors are often distinguished as either imaging instruments for estimates of surface and total column variables and sounding instruments used to derive vertical profiles, e.g., temperature and humidity. Microwave instruments have been flown as part of a number of past and current missions spanning 3 decades, including Special Sensor Microwave Imager (SSMI) and SSMI/Sounder (SSMI/S) by the Department of Defense; the TRMM microwave imager (TMI) and GPM microwave imager (GMI) by NASA; Advanced Microwave Scanning Radiometer (AMSR-E) on NASA's Aqua and AMSR-2 on GCOM-W1 from JAXA; Humidity Sounder for Brazil (HSB) on Aqua; Advanced Microwave Sounding Unit (AMSU), Microwave Humidity Sounder (MHS), and Advanced Technology Microwave Sounder (ATMS) on NOAA satellites; and Sounder for Probing Vertical Profiles of Humidity (SAPHIR) on Megha-Tropiques; to name a few.

Precipitation estimation has been a key focus of many of these past and current passive sensors, particularly TRMM and GPM. To estimate precipitation, algorithms exploit sensor measurement of the emission and scattering of microwave radiation by liquid and frozen hydrometeors, respectively. Relating rainfall to passive microwave brightness temperatures depends critically on the presence of a low emissivity water background. Therefore, techniques that are based on the emission of microwaves by rain drops and that provide the best estimates of surface rainfall are generally restricted to oceans and use frequencies below 40 GHz. Over land, surface emissivity is large and highly variable so that emission is a very weak source of precipitation information. Thus, over-land algorithms must take advantage of the scattering of microwave energy, detected at frequencies generally at or above 85 GHz, caused by atmospheric ice particles in clouds and precipitation. Lower frequencies near 85 GHz better detect precipitation-size particles in moderate and heavy precipitation and frequencies near 165 to 183 GHz are often useful for lighter rain, snowfall, and mixed-phase conditions (Hou et al. 2014, Panegrossi et al., 2017; Rysman et al., 2018). The disadvantage of these over-land algorithms for rainfall estimation is that the ice which produces the scattering signal is typically well above the surface and the near-surface rainfall must be assumed to have a similar distribution and magnitude as the ice aloft.

Ice clouds play an important role in the climate of Earth but represent a major uncertainty in models since their formation is less well understood than liquid clouds and the varying particle shapes and physical properties complicate their interaction with radiation (Stephens et al. 1990, Wendisch et al. 2005, Yang et al., 2015). The total amount of ice in high clouds per unit area (defined by the ice water path) in climate models can vary by as much as an order of magnitude (Waliser et al. 2009, 2016). Active radar systems, as described in section 7.1, and passive microwave sub-millimeter instruments provide data directly related to the total ice content within ice clouds. The ACCP radar can provide high vertical resolution measurements of the ice content in clouds over a narrow swath, with data needing to be collected over longer time periods and aggregated over larger spatial scales to reduce sampling errors and develop climatologies. Passive microwave sensors on the other hand can provide estimates of the total ice content over a wide swath (Fig. 7.4), with near global coverage on a daily basis, but at the cost of vertical profiling capability. Also, the radar measurements are heavily influenced by the size of the largest ice particles, while the passive measurements are more sensitive to the total mass. As a result, synergistic interpretation of active and passive measurements provides the best approach for characterizing the properties of high clouds. Having a range of passive microwave frequencies allows for characterizing the size distribution of ice particles since lower frequencies interact more strongly with larger particles and higher frequencies with smaller particles (Buehler et al. 2007, 2012).

For ACCP, passive microwave measurements fill several key roles: 1) to characterize the properties of ice clouds (O2, O3, and O4); 2) to provide estimates of precipitation at the surface (O3, O4, and O6); 3) to provide horizontal context for nadir-only or narrow-swath measurements from active sensors; and 4) to provide constraints on active-sensor retrievals of IWP, if spatial resolution comparable to the radars can be accommodated with the microwave sensor. Early in the study, it was clear that a GMI-like radiometer was well beyond the budget of ACCP and that various alternatives offering frequencies below 85 GHz would result in fields of view that were too large to be useful for science. As a result, the study focused on instruments with frequencies spanning the range of 85-880 GHz. These instruments will fulfil the roles above, although with less fidelity (compared to GMI) of precipitation measurements over oceans due to the lack of lower frequency (<40 GHz) channels. ACCP will rely on radiometers in the PoR (e.g., AMSR-3, WSF, MWI) for measurements of precipitation using these lower frequency channels.

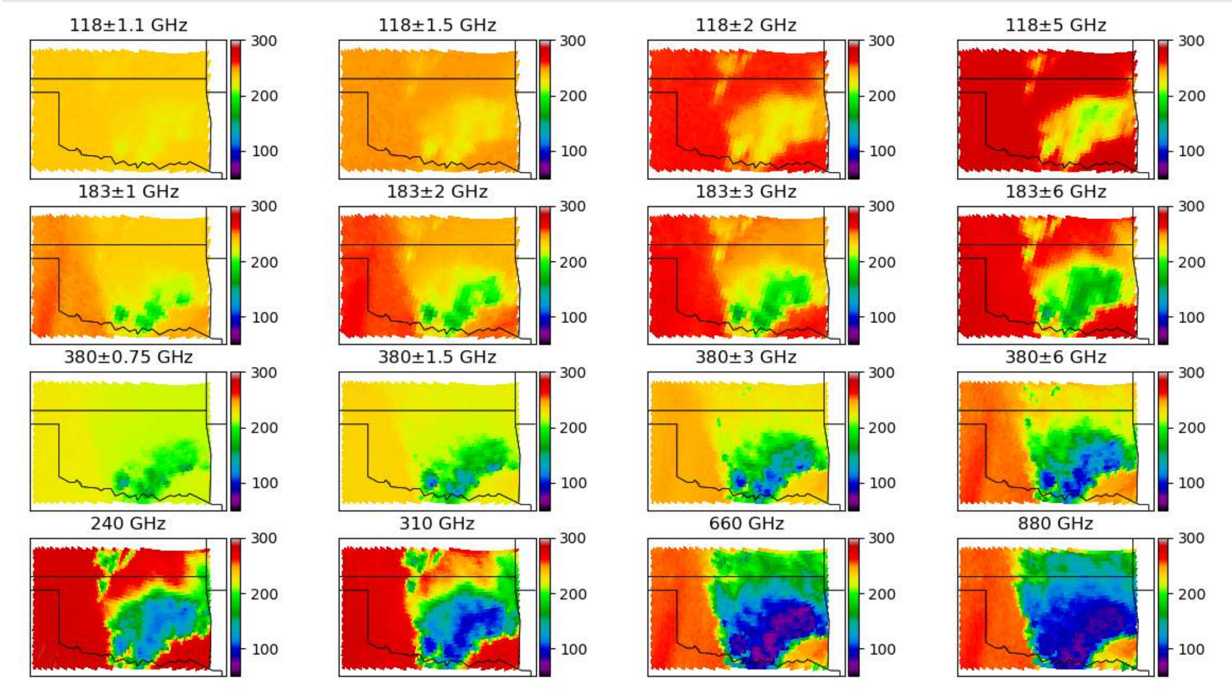


Figure 7.4. Simulated passive microwave observations for a case of a mesoscale convective system over Oklahoma for channels spanning 118 – 880 GHz. (Simulation and figure courtesy of J. Munchak).

7.3 Lidar

Lidar measurements of backscatter, depolarization, and extinction, acquired during both daytime and nighttime, provide critical profile information for studying aerosol and cloud impacts on climate, weather, and air quality. Spaceborne lidar provides high vertical resolution profiles of aerosol and cloud distributions that complement both active (radar) retrievals of cloud properties and passive (polarimeter) retrievals of aerosol properties. Satellite lidars such as Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) on the CALIPSO satellite and Cloud-Aerosol Transport System (CATS) on the ISS have provide essential measurements of aerosol and cloud vertical distributions (Winker et al. 2010, McGill et al. 2015).

The CALIOP and CATS spaceborne lidars use Nd:YAG lasers that emit light at both 532 nm and 1064 nm. These backscatter lidars measure the light backscattered by air molecules and particulates at these wavelengths. Both elastic backscatter lidars transmit polarized laser light and then separately measure the parallel and perpendicular components of the backscatter light. The ratio of these two components is the volume depolarization ratio, which is used to identify nonspherical particles such as dust and ice (Sassen and Cho 1992, Murayama et al. 2001). Depolarization measurements also provide a measure of the multiple scattering in water clouds (Hu et al. 2006). Additionally, lidar measurements at multiple wavelengths have sensitivity to particulate size (Oo and Holz 2011). Like CALIOP and CATS, the ACCP satellite lidars will also measure total attenuated backscatter and depolarization at 532 nm and 1064 nm.

Elastic backscatter lidars such as CALIPSO and CATS have a basic limitation when retrieving AOD and profiles of aerosol extinction. The fundamental measurement of these lidars is the profile of total *attenuated backscatter*: i.e., the product of the total (molecular + particulate) backscatter at each altitude and the two-way atmospheric transmission between that point and the lidar; therefore, it depends significantly on the attenuation due to overlying aerosol and clouds. Retrieving aerosol extinction and backscatter profiles requires solving one equation with two unknowns: particulate backscatter and particulate extinction. Consequently, for elastic backscatter lidars, additional information or constraints must be provided to relate particulate backscatter and extinction. This is often done by prescribing a value of the ratio of extinction to backscatter [lidar ratio or S_a) (Klett 1981, Fernald 1984) based on an inference of aerosol type. Uncertainty in the lidar ratio is the largest source of systematic error in the CALIOP operational aerosol extinction and optical depth retrievals (Rogers et al. 2014, Young et al. 2018). These systematic uncertainties also impact the retrieval of aerosol depolarization from the volume depolarization (Burton et al. 2013) and the wavelength dependence of backscatter that provides inferences of particle size. These systematic uncertainties are particularly large after the lidar beams have passed through overlying cloud and/or aerosol layers so the largest uncertainties in all products occur near the Earth's surface.

ACCP directly addresses this basic limitation by deploying an HSRL lidar to provide transformational advances well beyond CALIOP and CATS. An HSRL lidar provides significantly more accurate AOD, extinction profiles and other products by essentially measuring the attenuated molecular backscatter signal (i.e., product of the molecular backscatter and two-way transmission) separately from the total attenuated backscatter. The attenuated molecular backscatter can be directly inverted to retrieve the particulate extinction directly, and the ratio of the two channels provides particulate backscatter coefficient, which is a fully vertically resolved indicator of aerosol abundance, unlike attenuated backscatter. Because these simple operations do not require assumptions or additional information about the particulate properties, profiles of aerosol backscatter, extinction, and optical thickness can be obtained accurately throughout the atmosphere including below thin clouds. This is a major advance since CALIPSO measurements indicate that over half of aerosol retrieval opportunities contain additional uncertainty from overlying thin clouds. Additionally, CALIPSO and CATS are unable to detect a large portion of tenuous aerosol that leads to underestimates of direct radiative effects (Thorsen et al. 2017) that are the focus of ACCP's Objective 7. In contrast, ACCP HSRL measurements can detect tenuous aerosol missed by CALIOP and CATS. The highly accurate, calibrated, near-surface measurements of aerosol backscatter and extinction are required for quantifying aerosols within the PBL and assessing predictions of near-surface particulate concentrations (Objective 5).

Aerosol type information is contained in the lidar measurements of aerosol intensive properties (e.g., lidar ratio, wavelength dependence of backscatter, depolarization ratio) which vary with aerosol size, shape and composition. For example, the lidar ratio and wavelength dependence of backscatter contains information regarding particle size and composition and the depolarization ratio contains information regarding particle shape. The HSRL measurements provide the lidar ratio and also more accurate particulate depolarization and wavelength-dependent backscatter and so are a major advance in inferring aerosol type (Burton et al. 2012, Groß et al. 2012) and subsequently apportioning aerosol extinction and AOD to aerosol type. Aerosol classification using these measurements provides important insight into the origin of observed natural and anthropogenic aerosols, improves model predictions of PM2.5 and chemical composition (Dawson et al. 2017, Meskhidze et al. 2021) (Objective 5) and helps reduce uncertainties in aerosol direct radiative effects associated with aerosol optical properties (Objective 7) (Thorsen et al. 2021).

The HSRL for ACCP is designed with considerably higher vertical resolution (1 to 5 meters) than CALIOP (30 m) and CATS (60 m) at 532 nm. This higher vertical resolution, along with accurate measurements of depolarization to measure multiple scattering (Hu et al. 2006), will significantly improve retrievals of cloud top extinction. The combination of lidar retrievals of cloud top extinction and polarimeter retrievals of cloud drop radius (Alexandrov et al. 2012) can provide direct estimates of cloud drop number concentration at cloud top. The combination of high vertical resolution and HSRL capability also leads to major advances for studying ocean subsurface properties (see ocean box).

HSRL measurements in the UV (355 nm) provide additional important information that, when combined with the HSRL measurements at 532 nm and the backscatter measurements at 1064 nm, facilitate retrieving particle size and concentration (Burton et al. 2016) as shown using airborne data (Sawamura et al. 2017) and SIT A simulations of the ACCP multiwavelength HSRL measurements. Previous studies (Muller et al. 2007) as well as detailed simulations conducted by the SIT A found that this additional UV information also aids aerosol classification. The UV-VIS wavelength dependence of depolarization also provides information to help discriminate between smoke and dust (Burton et al. 2015) and non-spherical sea salt. HSRL measurements in the UV would also extend the ATLID measurements to be acquired by the EarthCare suite of instruments. Measurements in both the visible and UV would also help facilitate the use of the combined CALIOP, ATLID (EarthCare), and ACCP measurements to create a multidecade spaceborne lidar record to examine and constrain the cloud response to anthropogenic forcing (Chepfer et al. 2018).

An important addition to the suite of instruments in the inclined D1A architecture is a small but capable backscatter lidar. This lidar is based on the high repetition rate, low pulse energy, photon-counting approach to elastic backscatter lidar that was demonstrated in space by CATS (McGill et al. 2015, Yorks et al. 2016). CATS demonstrated that this technology can provide valuable cloud (Baray et al. 2019, Chepfer et al. 2019, Dolinar et al. 2020) and aerosol (Rajapakshe et al. 2017, Lu et al. 2018, O'Sullivan et al. 2020) science at relatively low cost. This lidar, when deployed in the ACCP inclined orbit, will provide cloud and aerosol measurements that complement the HSRL measurements in polar orbit. These backscatter lidar measurements in inclined orbit will provide measurements at different local times that, in combination with the HSRL measurements in polar orbit, will better observe diurnal changes in clouds and aerosols. This small lidar will provide better signal to noise ratio than CALIOP for both daytime and nighttime measurements and so will detect some tenuous aerosols missed by CALIOP. It will also measure both attenuated backscatter and volume depolarization at 532 and 1064 nm and provide cloud and aerosol layer heights, cloud phase, and some information regarding aerosol type. Measurements from this lidar, as well as the HSRL, will also be used to derive the height of the mixed layer, which is often a very good estimate of the Planetary Boundary Layer (PBL) height.

Another way that ACCP will provide transformational advances in aerosol retrievals well beyond the A train is the joint deployments of the HSRL and backscatter lidar with advanced, multiangle, multiwavelength polarimeters. Retrievals of aerosol properties using such combined datasets are significantly better that using either set alone; the lidar provides detailed vertical profile information and the polarimeter provides detailed column-averaged aerosol information. CALIOP retrievals of aerosol extinction profiles have used column AOD constraints to compute aerosol extinction and backscatter profiles that were significantly more accurate than operational CALIOP profiles that rely on inferences of the lidar ratio. Such constraints can be provided by retrievals of column AOD from passive sensors [e.g., MODIS (Burton et al. 2010)] and coincident radar (CloudSat) and lidar (CALIOP) signal returns from the sea surface to provide accurate estimates of the lidar calibration coefficient at both 532 nm and 1064 nm via the Synergized Optical Depth of Aerosols (SODA) technique (Josset et al. 2010; Painemal et al. 2019). Previous simulations (Burton et al. 2016), SIT A studies, and airborne lidar and polarimeter measurements (Xu et al. 2021) demonstrate how the combination of near simultaneous and collocated lidar and polarimeter measurements can provide more detailed information regarding particle size, concentration, and composition.

7.4 Polarimeter

Sunlight entering Earth's atmosphere is unpolarized. After being scattered by the atmosphere the unpolarized light from the sun is polarized to varying degrees depending on the properties of the scatterers themselves and the amount of multiple scattering experienced. This polarization property is evident when observing the angular pattern of scattered sunlight. The measurement of the degree of polarization represented in the angular pattern of sunlight transmitted to the Earth's surface has long been proposed as a way of monitoring the amount of aerosol in the atmosphere. The more recent focus has been on exploiting the polarization of reflected sunlight from polarimeters on orbiting satellites. This topic has advanced over the past 20 years with a number of polarimeters having been flown on Earth orbiting satellites and we now have a clear understanding of the information provided by these measurements (Fig. 7.5). Three incarnations of POLarization and Directionality of the Earth's Reflectances (POLDER) instrument have been flown on satellites. When implemented as part of the Polarization and Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations from a Lidar (PARASOL) microsatellite, POLDER has provided the longest satellite polarimeter record (2004-2013) thus far and has demonstrated how such observations can substantially improve aerosol data assimilation results including that related to aerosol size and absorption (Tsikerdekis et al., 2021). Another notable development is the 3MI polarimeter that is now part of the MetOp operational satellite sensor suite (Manolis et al. 2014).

The inherent advantages of multi- angle polarimetric measurements of scattered sunlight for extracting aerosol microphysical and optical properties is well documented (Hasekamp and Landgraf 2007; Mishchenko and Travis 1997) and these measurements are an important contribution to meeting the ACCP aerosol objectives. Polarized hyper-angular observations of clouds also provide unique information about water cloud droplet size distributions (Alexandrov et. al. 2012) and about the shape of ice-particles that constrain the scattering properties of ice crystals (Van Diedenhoven et al. 2012). The primary characteristics of polarization measurements that deliver their information content are a combination of both the spectral range, the multi-viewing-angle range and the accuracy of the polarimetric and radiometric observations. Ideally the spectral range should extend from the deep blue to the short-wave infrared (400-1650 nm; Wu et al. 2015), the angular range that is viewed should encompass a scattering angle range of 85-155° (Hasekamp and Landgraf 2007), there should be at least five viewing angles over that scattering angle range (Wu et al. 2015, Xu et al. 2017) and the polarimetric accuracy should be better than 0.5% (Hasekamp and Landgraf 2007, Knobelspiesse et al. 2012). The studies of both Wu et al. and Xu et al. are for a limited number of cases over the western United States and that longer

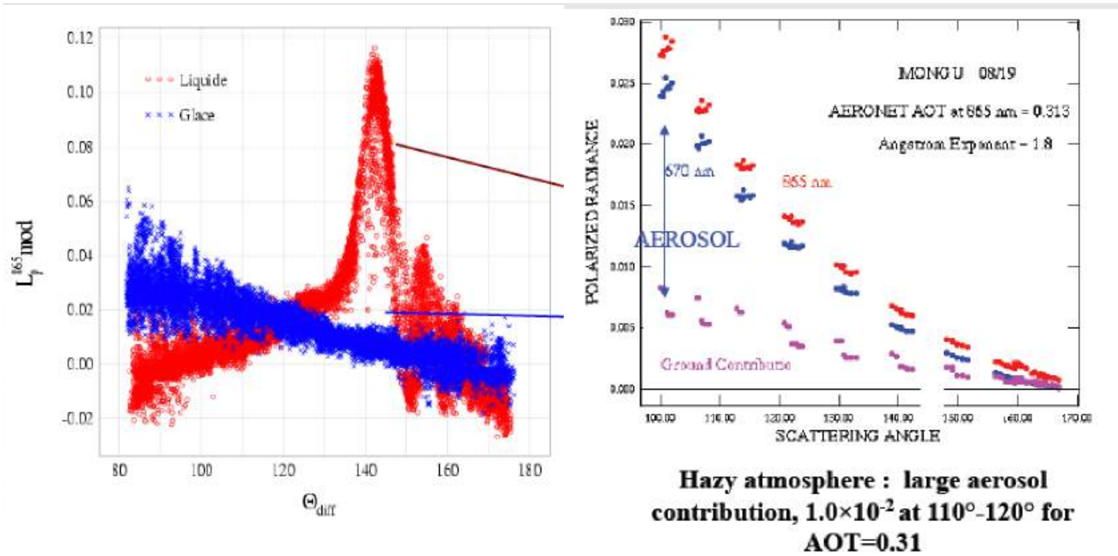


Figure 7.5. Two examples, one taken from 3MI (left) and another from POLDER (right) that hint at selected pieces of information contained in the angular pattern of polarized radiances scatterers from Earth's atmosphere and surface. The image to the left illustrates the sensitivity of the variation of the degree of linear polarization with scattering angle to the phase (liquid or ice and thus shape) of cloud scatterers clearly suggesting an ability to identify cloud top phase. The image to the right shows how the polarization of scattered light from aerosol substantially exceeds that from the land surface thus enabling the unambiguous identification and quantification of aerosol over land.

wavelength measurements may be valuable for detailed characterization of dust and more viewing angles would allow for the use of neutral points and ocean glint (Ottaviani et al. 2013) in retrieval algorithms. Polarization measurements that meet the requirements described above allow for aerosol retrievals that provide the AOD, Single Scattering Albedo (SSA), Aerosol Layer Height (ALH), effective radius, effective variance, complex refractive index and particle number column for both the fine and coarse mode as well as a shape parameter for the coarse mode with an accuracy that allows for the quantification of the aerosol radiative forcing (Mishchenko et al. 2004, da Silva et al. 2020, GCOS 2021).

ACCP proposes to take advantage both of the individual capabilities provided by polarimetric observations and of the synergy between lidar and polarimeter observations that improves upon the capabilities of either individual sensor. The polarimeter concepts under consideration are also an advance over past and current satellite sensors proposing both more spectral bands, more viewing angles and higher accuracy than previous spaceborne polarimeters.

7.5 Spectrometer

The reflection of sunlight by Earth to space is a process that exerts a basic control on Earth's climate through the way Earth differentially scatters and absorbs solar energy from place to place which is a basic forcing of the transport of heat and moisture poleward. The scattered sunlight also influences Earth's climate through the processes it shapes in the form of feedbacks that principally control the responses to external forcings of the climate system. The net solar radiation at the top of the atmosphere is balanced by the emission of longwave radiation to space with varying contributions from emission from the atmosphere and the Earth's surface. Clouds modulate this balance in complicated ways that can both add heat to the system by reducing the LW emitted to space and remove heat from the planet by enhancing its albedo. Aerosols also play a role both by directly affecting sunlight reflected to space and indirectly by altering the cloud microphysics and initiating precipitation. Insights about aerosol and cloud influences, including on cloud feedback processes and the forcing of climate by aerosol, are encoded in the spectral nature of the reflected solar radiation to space.

Measurements of spectrally resolved longwave emittance, visible and shortwave IR (VSWIR) reflectances contribute to the ACCP objectives in several important ways (Table 7.3). Contained in the spectral properties of reflected sunlight is important information about the scatterers themselves and the total energy of sunlight that is scattered. Similarly, cloud physics information is embedded in the signature of longwave emission, particularly in the atmospheric window of the longwave mid IR (LWMIR, 8 to 14 μm) and in the far IR range (FIR, 17 to 100 μm). The spectral characteristics of radiation scatter, absorbed and emitted is sensitive to particle properties including size, shape, composition and concentration. These sensitivities range with wavelength. For example, scattering of shorter wavelength solar radiation is sensitive to small aerosol particles as well as larger cloud particles. At the other end of the spectrum in the longwave LWMIR and FIR domain, radiation is particularly sensitive to larger ice crystals.

Spectrometer information contribute to ACCP objectives in the following ways 1) spectra provide constraints on cloud radiative process and related estimates of radiative fluxes, 2) spectra enhance our ability to provide scene discrimination, 3) they provide aerosol and cloud optical properties based on differing sensitivities to particle properties, and 4) provide other enhanced information such as the phase of water in clouds, total column water vapor (TCWV), particle size profiles in shallow clouds and deeper ice clouds among other properties. The measurement approach proposed is based on complementary measurements from a VSWIR spectrometer and a LWMIR/FIR that provides spectrally contiguous measurements as resolutions of 5-10nm in VSWIR, but much coarser in the longwave, typically ranging between 1 and 40μm with cloud information content contained effectively in about 8 narrow LWMIR/FIR bands. The advantages in measuring such spectral detail range from the higher spectral precision inherent to the spectral measurements in contrast to radiometry, and the improvements on information content extraction by a tighter and appropriate spectral fitting of the observations.

Table 7.3: Geophysical variables that will be addressed by VSWIR and LWMIR/FIR spectral measurements and their relation to ACCP objectives (from Stephens et al. 2021).

Geophysical Variable	ACCP Objectives	Comments / Relationship to other, in light blue for VSWIR and orange for LWMIR/FIR
Cloud droplet effective radius	O1, O6, O7, O8	• Mature algorithms provide r_e over the full swath complementing narrow swath polarimeter estimates. • Spectra offer potential to derive in-cloud r_e profile thereby reducing uncertainty in cloud droplet number concentration and LWP
Ice crystal particle size	O2, O8	• Strong sensitivity of FIR channels to effective sizes up to 70 μm, which is useful to study the initiation of precipitation • Swath extends nadir lidar and radar measurements

Cloud optical depth	O1, O2, O6, O7, O8	• High spatial resolution (~0.5km) improves non-uniformity bias in the larger footprint of the polarimetry and radar • Higher sensitivity for optically thin clouds (COD < 3) • With a similar penetration depth as lidar, not sensitive to lower layers of opaque clouds
Cloud Liquid Water Path	O1, O8	• Derived from the r_e and tau. • Spectra reduces uncertainty relative to imagery and profiles remove biases inherent to use of cloud top particle sizes
Ice Water Path	O2, O3, O4, O8	• Derived from effective size and COD • Heritage from GEO and spaceborne instruments (e.g. IIR) as part of PoR
Cloud Phase	O4	• Cloud Phase derived across broad swath compliments narrow swath lidar and polarimeter information • Spectral signature of liquid and ice refractive indices allow for phase discrimination
Cloud top Pressure	N/A	• Needed to derive cloud radiative effects • Mature techniques using O2 A-band absorption. • Swath complements nadir lidar measurements.
Cloud Geometric-Top Temperature	O2, O3, O4	• Direct measurement of cloud temperature from MIR channels
Areal Cloud Fraction	O1, O4, O7, O8	• Spectra increase accuracy relative to imagery by improved scene discrimination • High spatial resolution provides improved cloud boundaries compared to polarimeter and the imagery of the POR.
Aerosol optical depth	O3, O5, O6, O7, O8	• Spectra increase capability of aerosol typing and aerosol property retrievals. • Swath complements nadir lidar and polarimeter measurements
Aerosol fine mode optical depth	O5, O6, O7, O8	• Mature algorithms (e.g. MODIS) use spectral information to partition fine and coarse mode AOD.
Aerosol effective radius	O3, O5, O6, O7, O8	• Spectra provide aerosol size information
Cloud Radiative Effects	O2, O4	• Provides means to deduce broadband radiative effects by constraining bottom up deductions for broad band fluxes. Also provides much tighter constraints of radiation kernel estimates • Provides LW broadband radiances and spectral information
Column water vapor	O1	• Central to key questions related to convective initiation and aggregation • May help with understanding humidification effects on aerosol retrievals near clouds

		• Transmittance of FIR channels directly depend on the water vapor continuum and are useful to retrieve the water vapor amount, even in low quantity
Geophysical Variable	ACCP Objectives	Comments / Relationship to other
Cloud droplet effective radius	O1, O6, O7, O8	• Mature algorithms provide r_e over the full swath complementing narrow swath polarimeter estimates. • Spectra offer potential to derive in-cloud r_e profile thereby reducing uncertainty in cloud droplet number concentration and LWP
Cloud optical depth	O1, O2, O6, O7, O8	• High spatial resolution (~0.5km) improves non-uniformity bias in the larger footprint of the polarimetry and radar
Cloud Liquid Water Path	O1, O8	• Derived from the r_e and tau. • Spectra reduces uncertainty relative to imagery and profiles remove biases inherent to use of cloud top particle sizes
Cloud Phase	O4	• Cloud Phase derived across broad swath compliments narrow swath lidar and polarimeter information
Cloud top Pressure	N/A	• Needed to derive cloud radiative effects • Mature techniques using O2 A-band absorption. • Swath complements nadir lidar measurements.
Areal Cloud Fraction	O1, O4, O7, O8	• Spectra increase accuracy relative to imagery by improved scene discrimination • High spatial resolution provides improved cloud boundaries compared to polarimeter and the imagery of the POR.
Aerosol optical depth	O3, O5, O6, O7, O8	• Spectra increase capability of aerosol typing and aerosol property retrievals. • Swath complements nadir lidar and polarimeter measurements
Aerosol fine mode optical depth	O5, O6, O7, O8	• Mature algorithms (e.g. MODIS) use spectral information to partition fine and coarse mode AOD.
Aerosol effective radius	O3, O5, O6, O7, O8	• Spectra provide aerosol size information
Cloud Radiative Effects	O2, O4	• Provides means to deduce broadband radiative effects by constraining bottom up deductions for broad band fluxes. Also provides much tighter constraints of radiation kernel estimates
Column water vapor	O1	• Central to key questions related to convective initiation and aggregation • May help with understanding humidification effects on aerosol retrievals near clouds

The need to relate broad band radiative fluxes to the cloud and aerosol properties obtained from the measurements provided by different sensors being proposed for ACCP is central to several ACCP objectives. The desire to examine these relationships on the sub-kilometer to kilometer scale more characteristic of clouds and aerosol plumes and more typical of the cloud information to be provided by ACCP measurements is a challenge given that the spatial coarseness of the available single footprint derived flux data of CERES and proposed for the Libera mission expected in the ACCP time frame is approximately 20 km. The integration of spectral data from the VSWIR and LWMIR/FIR spectrometers not only provides a meaningful way of deriving broadband radiances and then fluxes on this finer scale, but more importantly these spectral measurements offer a more direct way of differentiating responses of these fluxes to changes in aerosol and cloud properties. This is an essential step in providing meaningful observational constraints either on aerosol-radiative effects or on radiative kernels which expresses the sensitivity of the fluxes to changes in given cloud properties and is an important tool in quantitative analyses of cloud feedback.

The value of SVWIR spectrally resolved measurements can be underscored with reference to Fig. 7.6. It illustrates the spectral character of the shortwave column absorption derived from above and below water and ice cloud spectrometer measurements (a) and cloud radiative effect (SWCRE) expressed in the form of both spectral reflectance differences and broadband flux differences both being differences between reflected radiation from cloudy and clear skies (b). The latter are from model simulations that cluster the simulated spectra by the varying cloud types identified. The broadband SWCRE values (provided in the legend inset) are instantaneous at the time of satellite overpass based on an equator crossing (1330 local time). The spectra shown differentiate the clusters of different cloud types and reveal how differences in both column absorption and differences between the clusters of different cloud types emerge more clearly in the spectra. For example, the changes to SWCRE spectra at visible wavelengths, such as at 0.5μm, reflects the sensitivity of the reflected flux to cloud optical depth. The high and low cloud example, labelled spectra f and h, are of clouds of the same optical depth and thus same visible SWCRE yet the broadband SWCRE differ by almost 50 Wm^{-2}. This underscores the point that factors other than optical depth obviously contribute to this broadband SWCRE difference. Similarly, the character of shortwave absorption by cloud in (a) is dramatically different between high and low cloud.

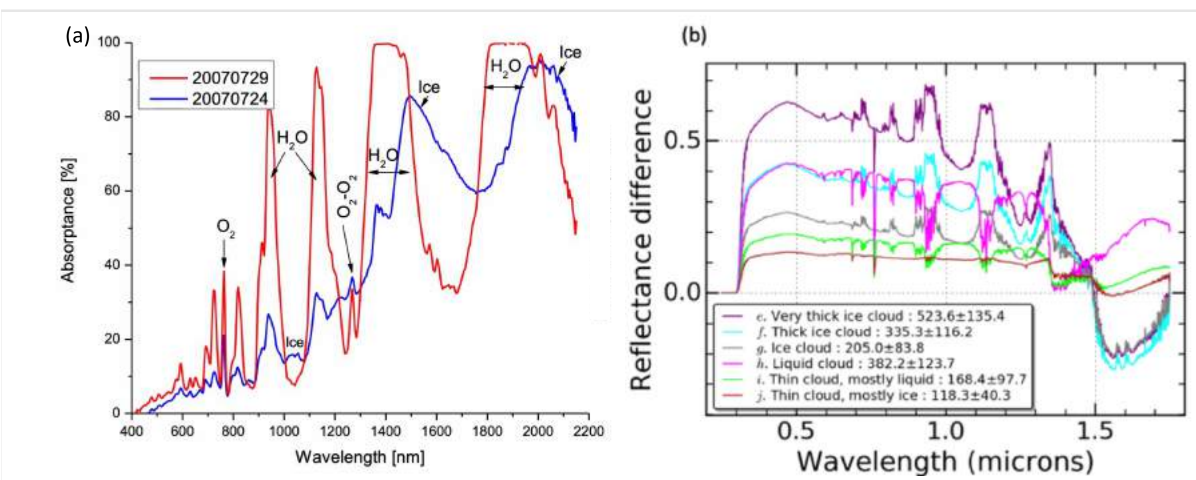


Figure 7.6. (a) Spectrally resolved estimates of SW absorption from airborne spectrometer measurements (add ref) for low (water) and high (ice) clouds (adapted from Schmidt and Pilewskie, 2012). (b) The mean spectral SWCRE (all sky minus clear) for computed SCIAMACHY- like reflectance spectra belonging to six cloud clusters. To the right of the colon in the legend is the mean broadband SWCRE of the given cluster with one standard deviation (Wm^{-2}). (From Gristey et al. 2019)

Quantifying the influence of cloud height changes on SW fluxes broadly requires VSWIR spectral measurements.

In the LWMIR/FIR, Fig. 7.7 shows the strong dependence of ice cloud reflectivity (single scattering albedo ω) and emissivity (1-ω) on wavelength and particle size. Accordingly, the observed brightness temperature of ice clouds is an acute function of wavelength, ice crystal size and shape, and ice water content or optical depth. The highly nonlinear physical processes controlling the cloud properties and their radiative forcing are a major challenge for reliable parameterization in atmospheric model, as they determine the ability of clouds to alter the energy balance of the atmosphere. By measuring simultaneously key radiative sources, the cause of perturbations and the resulting effect on thermal emission, the spectrometers closely meet many mission objectives, allowing closing the information loop acquired by the ACCP suite of instruments.

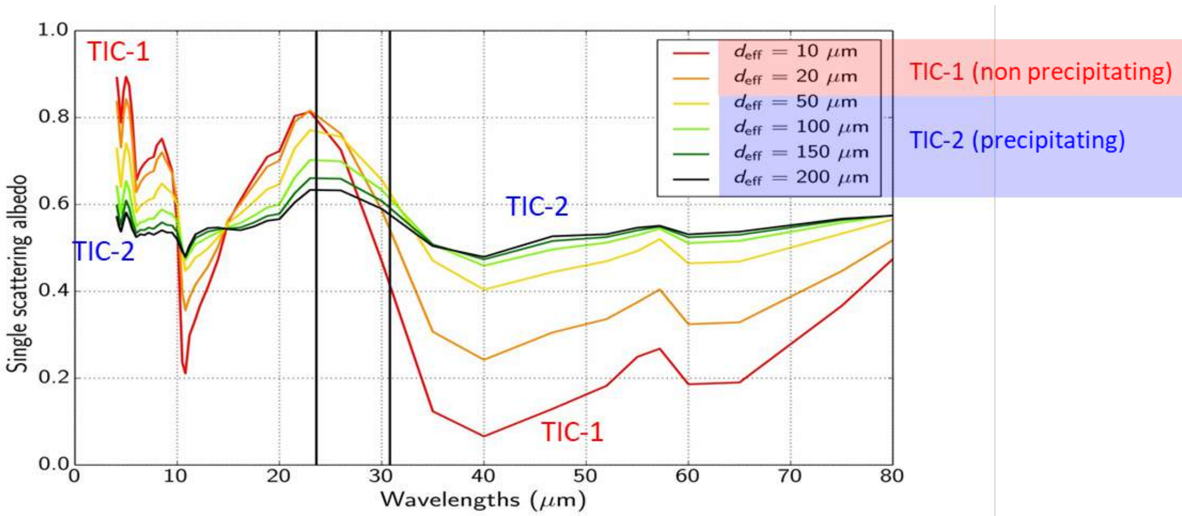


Figure 7.7. Spectral dependency of LWMIR/FIR single scattering albedo of ice cloud variation between 6 and 80μm. The figure shows the typical range of cloud single scattering albedo spectra as a function of ice crystal size. Crystals larger than ~40 μm initiate precipitation. Smaller crystal tends to cool and destabilize convective storms while large crystal cool deeper in thin ice clouds layers. (Libois and Blanchet, 2017)

By monitoring the far IR domain (Fig. 7.8), the LWMIR/FIR spectrometer covers a critical range in the Earth's thermal emission, where a major portion (50% to 70%) of the Earth's atmosphere and surface energy lost to space and adds genuinely new information to the suite of ACCP instruments, especially in colder air, near the tropopause and in Polar Regions. Due to the gradual strengthening of the water vapor continuum in the longwave, the LWMIR/FIR permits a coarse profiling of water vapor and clouds (Fig. 7.8). The wide span of the water vapor continuum across far IR, parsed with multiple micro-windows and absorption lines, favors detection of low water vapor amounts, otherwise hard to measure. The spectrometer is appropriate for the evaluation of the atmospheric water cycle and water budgets in clear air, clouds and light precipitation, such as *cirrus fibratus* or diamond dust in Polar Regions and contrails from air traffic aerosol and gas emissions.

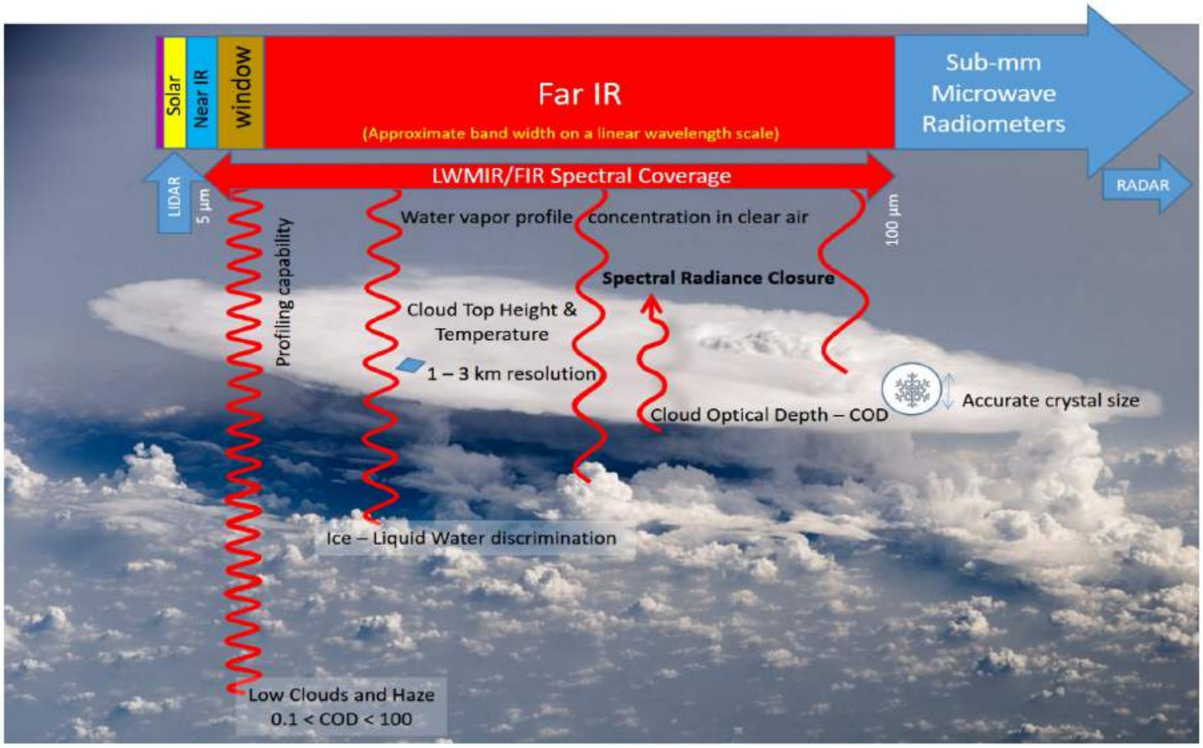


Figure 7.8. Spectral domain of LWMIR/FIR spectrometer bridging the critical gap of terrestrial emission at wavelengths between 5 and 100µm. Shorter thermal emission wavelengths in the atmospheric window are mostly transparent in clear sky, while longer wavelengths progressively reach higher altitudes, allowing for profiling. Labels show some of the key geophysical variables probed by the longwave spectrometer. (Cloud picture: NASA).

7.6 Time-Differenced Measurements

With the emerging and demonstrated capabilities of miniaturized sensors like Raincube, and the lowering cost of small satellite platforms, it has now become feasible to consider employing a more distributed approach to address atmospheric processes. Three such concepts were considered in the ACCP study in which sensors were proposed to be flown in a clustered formation to observe very fast changes in clouds and convection. The concepts each exploited the time difference (Δt) between measurements as an important added dimension to address process.

7.6.1 Tandem Stereo Cameras

The Cloud Dynamics Imager (CDI) concept uses a pair of high resolution (better than ~50 m) stereo images to derive cloud heights and motions from two satellites at two different times, as depicted below in Fig. 7.9. Collection of the stereo-image pairs are separated in time by 30 to 60 seconds, the time it takes the two satellites to pass overhead. From each image pair, the height of clouds, smoke plumes, and other objects are determined using the observed parallax (the apparent shift in position of an object in two images observed at different view angles). The object motion (velocity) is then obtained from the change in position between the image pairs. This concept builds upon an over 20-year heritage of stereo-imaging from space by the NASA Multiangle Imaging Spectro-Radiometer (MISR). However, CDI uses two satellites and finer resolution

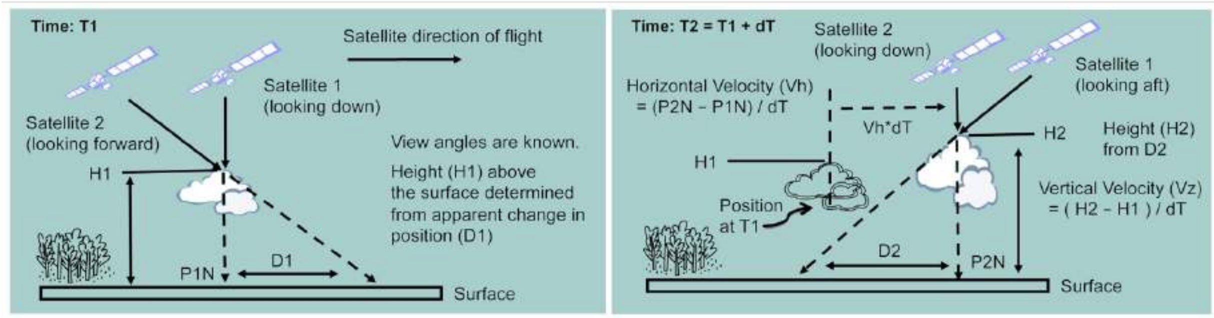


Figure 7.9. Illustration of tandem stereo imaging. Two view angles (one nadir and one forward or one aftward view) from tandem spacecraft provide instantaneous stereoscopic heights and time-lapse imagery for retrieval of cloud horizontal and vertical velocities. Figure courtesy of Roger Marchand, Univ. of Washington.

imagery to enable accurate measurement of vertical motion of clouds, which can't be done with MISR.

Figure 7.10 shows an example of what a subset of CDI imagery will look like for a field of subtropical cumulus. The high image resolution is needed to measure vertical motions to about 1 m s^{-1} (or better). This image resolution is significantly finer than that used by weather and most other climate satellites (typically 0.5 to 1 km). In combination with other instruments, CDI data will advance NASA earth science objectives by enabling scientists to study better the shape, size, and other properties of clouds (such as cloud water content), and how these properties relate to cloud horizontal and vertical motions. In Fig. 7.10, for example, the CDI data will allow scientist to determine which clouds are growing and getting higher and which clouds are decaying. In this way they can study the cloud population dynamics and learn how the properties of growing and decaying clouds change with surface and atmospheric conditions, including the amount of aerosols (small particles).

In addition, it is not just cumulus clouds, big or small. Stratocumulus cloud decks cover large areas of the ocean and are of critical importance to climate because of the large amount of sunlight they reflect back to space. Much of the uncertainty in current climate model projections is due to

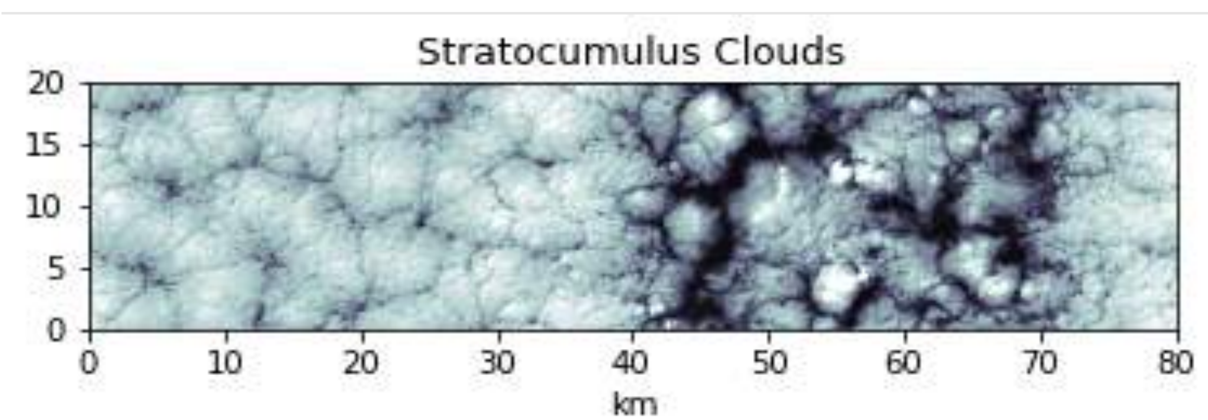


Figure 7.10. Example of Stratocumulus clouds as will be observed by CDI. Figure created bu Matt Lebsock, JPL. Figure created by Matt Lebsock, JPL. Simulation data provided by Anthony Davis, Marcin Kurowski, and Linda Forster, JPL.

uncertainties in how stratocumulus will change in the future. To better understand how these clouds will change scientists need to better measure the motions within them. Stratocumulus clouds are usually observed to have visible cellular structures on horizontal scales of 10 to 50 km (Fig. 7.11). These structures are imprints of the motions within the clouds that scientists need to better understand. CDI will measure the strength of the stratocumulus cloud-top motions and allow scientist to learn how cloud shapes and properties depend on cloud motions and how these relationships change with surface and atmospheric conditions.

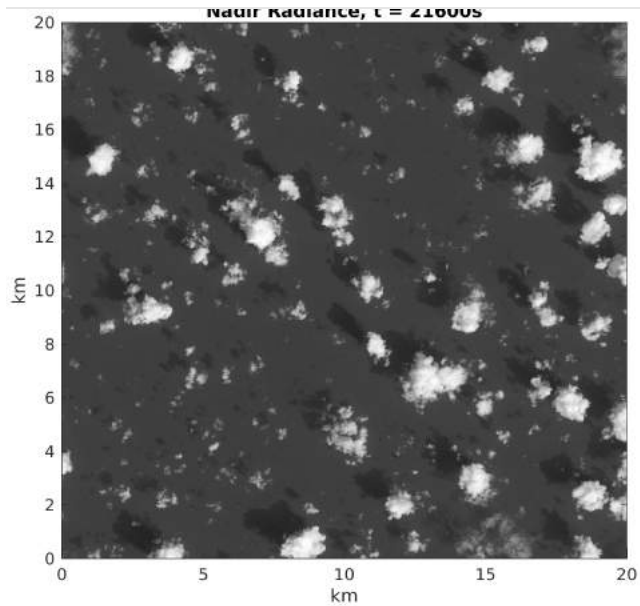


Figure 7.11. Example of subtropical cumulus field as will be observed by CDI. Figure created by Roger Marchand, Univ. of Washington. Simulation data provided by Anthony Davis, Marcin Kurowski, and Linda Forster, JPL.

7.6.1 Tandem Radiometers

Microwave radiometers and radars in low Earth orbit (LEO) provide the most direct estimates of condensed water in clouds, but owing to their long wavelengths (relative to visible light), they must be placed on LEO to achieve the necessary spatial resolution, and thus their temporal sampling is quite limited. Indeed, a single LEO instrument will very rarely observe a weather system more than once during the lifetime of the system. On the rare occasion that a single instrument may revisit a storm on two consecutive orbits, the visits are nevertheless separated by the typical amount of time it takes the satellite to complete one orbit, i.e., ~90 minutes. During this revisit gap, the cloud will typically have undergone dramatic change, observed only by geostationary satellites orbiting at much higher altitudes (which do not carry instruments capable of “seeing” inside the clouds).

Recent technological advances have enabled the design of miniaturized microwave instruments that are quite capable and, at the same time, inexpensive enough to consider the formation of a convoy of identical radars or radiometers in low-Earth orbit (illustrated in Fig. 7.12), separated in time by $\Delta t \sim 1$ minute, the temporal scale required to observe the highly nonlinear cloud dynamics present in convective updrafts. The observations are conceptually similar to the loops that are currently obtained from ground weather radar, as well as geostationary imagery, which readily show the evolution of precipitation (in the radar case) or cloud tops (in the imagery case) over minutes. The satellite convoys overcome the limitations of geostationary imagers (sensitive only to the very top of the clouds) and those of ground radar (very limited spatial coverage). Because each satellite instrument is sensitive to the 3-dimensional distribution of condensed water within its field of view, the convoy is sensitive to the change in this condensed water over the minute(s) separating the convoy members.

The sensitivity to the minute-scale changes in the condensed water can be exploited to derive the strength of the upward vertical transport in the cloud, and its variability within the storm. The reason becomes clear when one examines the three components of the change in the condensed water field, namely the horizontal motion (u and v), the upward velocity (w) in the cloud, and the corresponding change in the mass of condensed water ΔM. The advection (u and v) during the interval separating two consecutive convoy members can be accounted for by correlating the spatial intensity patterns in the consecutive observations, and the change ΔM (in a saturated column of cloud) turns out to be proportional to the vertical velocity w (essentially because upward motion moves a saturated air parcel up to a location with lower temperature, in the troposphere, forcing more condensation – and, conversely, condensation produces "latent" heating, reducing the density of the parcel and enhancing the buoyant upward motion). Thus, consecutive observations can be used to detect – and estimate the magnitude of – the upward vertical velocity, if the change in condensed water mass is sufficiently large to be detectable unambiguously in the microwave measurements.

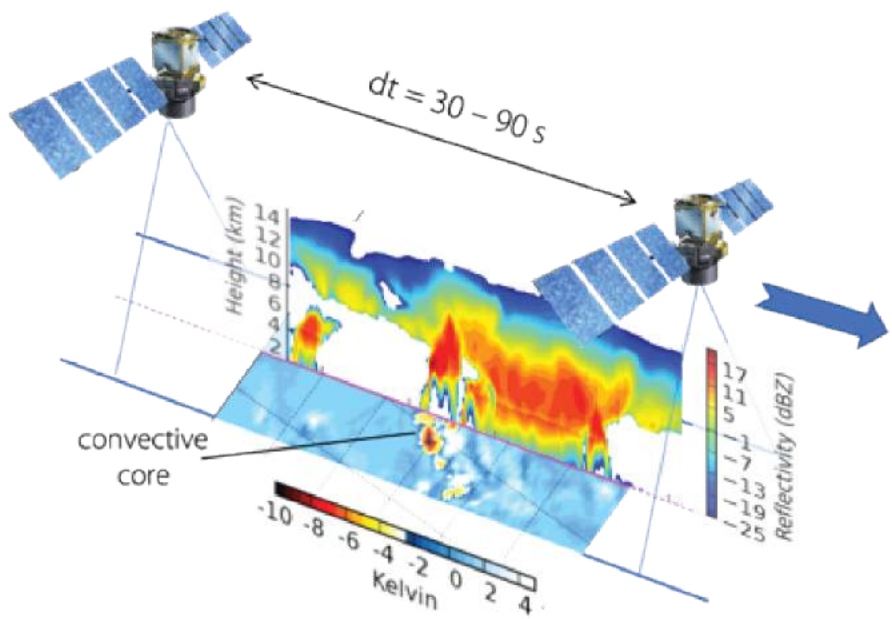


Figure 7.12. Schematic of a convoy of satellites carrying passive microwave instruments providing the horizontal map. The map reveals the intensity of in-cloud upward motion associated to condensed water from time differences of the brightness temperature (in Kelvin) measured at 183GHz. The vertical cross-section is the vertically resolved concentration of hydrometeors (reflectivity) as provided by a radar (in the present case, the CloudSat radar). Figure courtesy of Helene Brogniez, Laboratoire Atmospheres, Observations Spatiales.

This characterization of updraft intensity is quite complementary to the information retrieved from line-of-sight Doppler radar in two ways. First, while Doppler radar can provide estimates of the instantaneous motion during the milli-second-scale measurement interval, it cannot provide information as to how constant this value may, or more typically may not be, over the temporal resolutions of our best weather models, which range from tens of seconds, up to minutes. The minute(s) scale of convoy-derived estimates makes them more readily comparable with modeled vertical transport. Secondly, Doppler is sensitive to a convolution of the air motion with the fall velocity of hydrometeors, the integral being weighted by the radar reflectivity of the hydrometeors, which adds intrinsic uncertainty to the retrieval of air motion when the hydrometeor shapes and sizes are not known. Estimates of in-cloud vertical transport from satellite convoys are derived directly from the observations, and hence are not sensitive to hydrometeor fall speed. Of course, using passive mm-wave radiometers, it is not possible to resolve the vertical structure of the vertical motion as finely as a Doppler radar can. Instead, only average vertical transport, column-maximum value (see Fig. 7.13) and the vertical location of the maximum value can be retrieved,

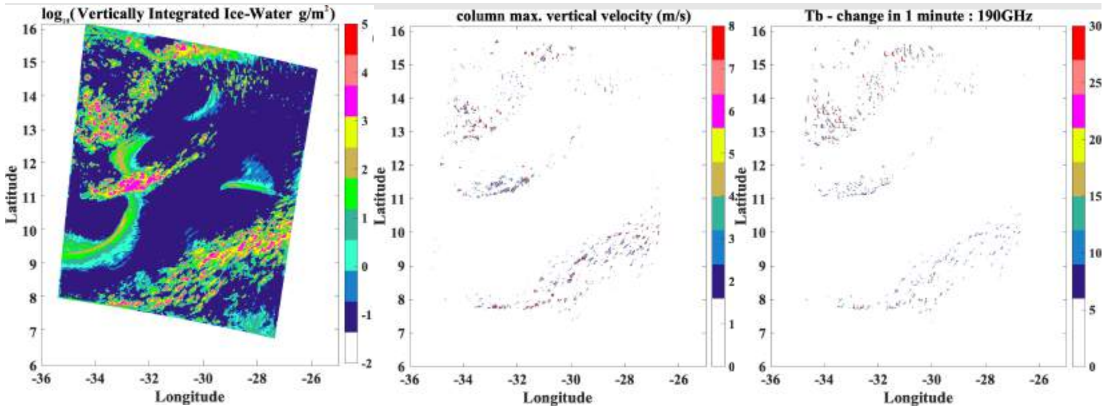


Figure 7.13. The left panel shows the values of the vertically integrated ice water content at 06:00 UTC on 6 September 2003 in a simulation of Hurricane Isabel initialized on 5 September 2003 at 12:00 UTC (the storm became a category 1 hurricane the following day). The middle panel shows the values of the column-maximum vertical velocity, and the right panel shows the values of the change in the brightness temperatures at 190 GHz calculated from the simulation output. The simulation was conducted using the community Weather Research and Forecasting model in a 5-nested-grids configuration, with horizontal resolutions of 12, 4, 1.333, 0.444 and 0.115 km. Figure courtesy of Ziad Haddad, JPL.

but these vertically coarser quantities can be retrieved over a swath that is hundreds of kilometers wide, much wider than any LEO radar can hope to capture, and thus has potential to be used for many applications (aviation weather, severe storm forecasting, mesoscale numerical weather prediction) that might not benefit as much from a narrow radar swath. Thus, the observations from a convoy of radiometers should cover a very large portion – if not all – of any storm it overflies.

Retrieval performance can be quantified using cloud-permitting simulations, which indicate that vertical transport above about 2 m s^{-1} in cloud condensed-water concentrations of at least 0.05 g m^{-3} is detectable by a convoy of radars or a convoy of multi-channel microwave radiometers as long as the time separation between convoy members is greater than about 90 seconds. Longer time separations can be entertained to improve this sensitivity, though Δt values greater than 2 minutes cannot resolve the non-stationarity of typical updrafts. In fact, the most intense updrafts are non-stationary over shorter durations and are therefore best captured using a Δt value between 30 and 60 seconds. Figure 7.13 illustrates the relation between the change in 190 GHz brightness temperatures over 1 minute and the column vertical velocity over a cloud-permitting simulation of the tropical depression that became Hurricane Isabel 24 hours after the time of the simulated values illustrated in the figure.

7.6.2 Tandem Radars

A general concept for a radar dt measurement approach is illustrated Figure 7.14. In this hypothetical example, a constellation of three small satellites each flying a miniature, nadir-pointing Ka-band atmospheric radar spaced respectively 30 and 90 seconds apart, for example, provides the new dimension to the observations – one of time. For this case, three time-difference baselines provide the rates of change of convection from weaker (120 s) to the most intense (30s) systems. The principal measurement delivered by each radar of this constellation is the range-resolved power returned from atmospheric scatterers (hydrometeors) expressed in terms of a radar reflectivity (Z) factor. The measurement approach, however, also delivers an additional profile of information in the form of a reflectivity difference ΔZ. While each profile of Z contains

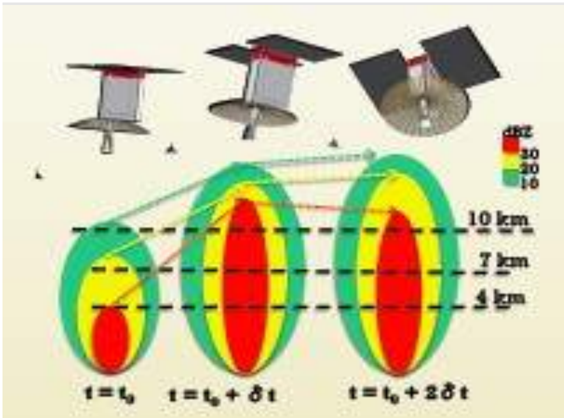


Figure. 7.14. A schematic depiction of a three-satellite cluster observing a growing convective cloud. Each profile would be matched to the preceding profile collected *d*t seconds before it. One concept being considered is for *d*t=30 and 90s. From Stephens et al. 2020.

information about convective strength, precipitation and hydrometeor mass to varying degrees, the time-differenced reflectivity measurements, by contrast, provide information about rates of change of condensed mass, a measure of vertical motion as well as other information that can be interpreted in terms of convective vertical transport as described below.

Radar reflectivity *Z* itself traditionally provides information about the mass of condensed water *M* in the radar volume (cloud or rain water content). Time difference measurements of Z (ΔZ) relate to rates of change of *M* in the volume in a much more direct and more accurate way than does *Z* relate to *M*. The vertical profile of this time rate of change of *M*, also unique to the radar Δ*t* approach, is a central measure of detrainment of ice from convective updrafts into anvil high clouds and potentially important to the O2 objective. Furthermore, the relation between time differenced radar measurements and vertical motion of hydrometeors can be conceptually understood in terms of measuring the movement in height of Z surfaces over the time. Although there are a couple of factors that can complicate this simple interpretation as vertical advection, a more formal analysis of the relation between the *d*t observations and vertical motion *w* is described in Stephens et al., (2020) and shows how the bulk relationship between ΔZ and *w* remains essentially robust and valid over a range of consistent typical of tropical convection. Furthermore, the combination of condensed mass and the vertical motion of it contained in the combination of Z and ΔZ profiles provide a measure of the product of mass *M* and its motion *w,* an expression of the mass flux of condensed water. This again is another important as aspect of radar Δ*t* measurements offering unique insights on the profiles of vertical transport associated with deep convection.

8. Development of the ACCP Space-Based Measurement Approach

8.1 The Instrument Library

An important mandate imposed on the study team was that instruments would not be designed from scratch to meet science requirements but would instead be competed among a set of reasonably mature existing technologies. A request for information (RFI) was put out to obtain information on instrument concepts (e.g., instrument capabilities, accuracy/precision, horizontal/vertical resolution, frequencies, mass, weight, power, maturity, etc.) that could be evaluated against desired science capabilities. The RFI responses were collected within documents referred to collectively as the instrument library. A high-level summary of these capabilities for different instrument types is given in Table 8.1 that focuses on specific characteristics. For example, for radar, the frequencies and presence or absence of Doppler capability is indicated in the first column. The instruments ranged from relatively inexpensive smallsat sensors that might potentially be inadequate for achieving the science objectives to highly capable but expensive instruments that moved architectures beyond the cost cap, with varying capabilities and costs in between. Balancing capabilities and costs was central to architecture design.

Table 8.1. High-level summary of the ACCP instrument library. For radar, the entries indicate the available frequencies, whether they use single- (-d) or dual-antenna (-D, DPCA) approaches for Doppler, and whether wide-swath capability is available. For passive microwave radiometers, the available frequencies are indicated. For lidars, we show the available channels and whether they have HSRL or backscatter (BS) capability. The polarimeter column shows the number of channels and angles while the spectrometer column shows the frequencies and number of channels. The Other column indicates other technologies that were considered in the study.

Radar	Radiometer	Lidar	Polarimeter	Spectrometer	Other
W-D, Ka-D, Ku-D W-d, Ka-d, Ku-d W-D, Ka-D W-d, Ka-D W-d, Ka-d Ka, Ku-d W, Ka Ka, Ku W-d Ka-D Ku-D, wide swath Ku-d, wide swath Ku-d W Ka Ku	11, 19, 24, 37, 89, 166, 183 GHz 11, 19, 24, 37, 89 24, 31, 55, 89, 166, 183 19, 24, 34 118, 183 87, 164, 174, 178, 181 118, 183, 240, 310, 380, 660, 880 883 183 183, 326 183, 326, 664 89, 183, 326 670 220, 680 91, 118, 183, 205	355 HSRL, 532 HSRL, 1064 BS 355 HSRL, 532 HSRL 532 HSRL, 1064 BS 355 HSRL, 532 BS, 1064 BS 532 BS, 1064 BS 1064 BS	14 channels, 5 angles 14 channels, 5-9 angles Hyperspectral, 1 angle Hyperspectral, 5 angles 10 channels, 60 angles 11 channels, 60 angles 12 channels, 60 angles 15 channels, 60 angles 9 channels, 255 angles Channels in VIS, VNIR, SWIR	LWIR, 3 channels VIS/NIR/SWIR hyperspectral LWUV/VIS/NIR/SWIR hyperspectral LWIR/FIR, 8 channels	Tandem stereo cameras Aerosol Limb Imager Moisture Limb Imager Radio Occultation

8.2 Architecture Construction Workshops and Design Centers

8.2.1 The requirement for polar orbit

ACCP was designed to focus on a balance between three DS science questions (convection, aerosols, and climate; section 3) and 8 science objectives (section 4). Polar regions are critical to Earth's energy budget and projections of climate change. The DS climate sensitivity and feedback question directly relates to ACCP objectives O1, O2, O4, O7, and O8, and each would be significantly impaired if polar regions are not sampled. Mixed-phase low clouds and aerosol-cloud interactions strongly impact cloud radiative effects and are poorly represented in climate models, as described in sections 4.4 and 4.8. Cloud amount and macrophysical characteristics, as well as estimates of snowfall, are important to sea-ice trends and ice mass balance in polar regions. Consequently, measurements from a polar orbit are viewed as being of critical importance to ACCP.

8.2.2 The motivation for an inclined orbit

Measurements from an inclined orbit connect the diurnal cycle to a broader process context over multiple time scales. The diurnal cycle is fundamental to the DS question on convection and measurements of rainfall from TRMM and GPM have made important contributions to this problem. TRMM provided limited information on clouds from the Visible and Infrared Scanner (VIRS) and on the radiative energy budget from the Clouds and Earth's Radiant Energy (CERES) instrument; however, CERES lasted less one year of TRMM's ~17-year-long lifetime. TRMM and GPM lacked important information on clouds and aerosols that can be provided by lidars and cloud radars, so ACCP presents a unique opportunity to examine the diurnal variability of coupled aerosol-cloud-precipitation processes and properties.

ACCP's interest in the diurnal cycle relates to more than just the timing of convection. Important phasing between convection, high clouds and upper tropospheric moistening exists (Box GEO). This process of moistening the upper troposphere by deep convection through the production of high clouds is influential to processes that play out over a range of time scales. Daily to sub-seasonal time scales are also important, including processes related to local destabilization, formation of ensembles of convective systems, and environmental restoration. On longer time scales, interannual modes are represented by coupled dynamical-radiative-convective feedback systems. Observing the diurnal evolution of convection significantly enhances our ability to link environmental thermodynamic conditions to variations in convective dynamics and microphysics.

Aerosol measurements on an inclined orbit allow us to explore diurnal variations in aerosol emissions and surface concentrations; diurnal evolution of aerosol removal, redistribution and humidification; and diurnal PBL dynamics. The CATS lidar (2015-2017) has provided the only diurnally varying information on clouds and aerosol profiles to date. Advancements in ACCP are likely through coupling of improved CATS-like measurements with cloud and precipitation Doppler radar capabilities and a polarimeter for better constrained aerosol measurements.

8.2.3 Architecture formulation

The team was tasked with exploring a wide range of potential architectures, from large single satellites to multiple medium-sized satellites to constellations of SmallSats. These architectures drew from the instrument library (section 8.1) that provided a wealth of information on potential sensors with varying capabilities and costs. To guide architecture construction, the ACCP SATM established a set of objectives and desired capabilities, with core technologies including multi-frequency radar, lidar, passive microwave radiometer, polarimeter, and spectrometer. In addition to inclusion of instantaneous measurements from single sensors, consideration was given to flying two or more identical sensors in order to address rapidly changing processes on time scales of minutes; this approach was often referred to as Delta-t (Δt) measurements and typically included radars, radiometers, and stereo cameras, as described in section 7.6.

To explore a range of architectures quickly, the team conducted a set of Architecture Construction Workshops (ACWs) at JPL in 2019. The goal of the ACWs was to estimate very high-level costs using parametric cost models for instruments, known prices for standard spacecraft buses (rather than custom-built spacecraft buses) and launches, and estimated ground-system costs scaled according to expected science data volume. Funds were also set aside for suborbital activities, science team, and other elements that could not be addressed as part of the ACWs, but ultimately had to be included as part of the total budget. A key advantage of the ACWs was that it quickly reset expectations of the scope of instrument capabilities that could be accommodated within the budget cap. As a result, the team explored tradeoffs between large-mass, high-power, high-capability sensors and low-mass, low-power, moderate-capability SmallSat sensors. Once constellations were defined and costed, small perturbations to these architectures could be costed fairly easily.

A second round of architecture construction was done through Collaboration Design Centers (CDCs) at multiple NASA centers. The CDCs performed much higher fidelity cost estimates for instruments based on instrument master equipment lists (descriptions of all components that make up the instruments) rather than using parametric cost models; more deeply explored the layout of instruments on spacecraft buses rather than a general determination of size and power needs; and conducted a deeper analysis of data downlink and ground system needs. While for ACWs, an analysis of an architecture was completed in a matter of hours, for CDCs an architecture was completed only after several days of analysis. As a result, fewer architectures could be examined by CDCs. To optimize the CDC effort, the team ACCP team examined lessons learned from the ACWs and qualitative science and applications benefits of the ACW architectures to prioritize architecture designs for the CDCs. As with the ACWs, once several architectures had been examined via the CDCs, small perturbations on these designs could be costed without conducting additional CDCs. Architectures developed during the CDCs were subjected to a science and applications benefit analysis that is described in the next section and eventually led to the selection to the final recommended architecture.

8.3 Quantitative Evaluation of Science Benefit

8.3.1 The Value Framework

The ACCP pre-formulation study had all the trademarks of a complex, multi-objective, multi-criteria decision problem. The study team had to design architectures that satisfied multiple science goals and their associated science objectives, while responding to potentially enabled applications and programmatic considerations. These candidate architectures were defined by combining seven types of sensors, for which 89 submissions were received in response to the initial Request for Information issued by the team. Many platforms, launch vehicles, and ground system options were also considered, leading to more than 100 alternative architecture concepts to assess.

The complexity of the study was amplified by the involvement of stakeholders from 6 NASA centers, 4 international partners, and many universities in the definition and assessment of the candidate architectures, introducing multiple value systems and varying priorities to reconcile. At the onset of the study, it became rapidly apparent that a heuristic-only approach would be insufficient for a study of this scope and that a structured, traceable, and transparent approach was required to be responsive to this complex decision landscape. This prompted the development of the ACCP Value Framework, which was designed to enable the strategic assessment of the candidate architectures (Fig. 8.1).

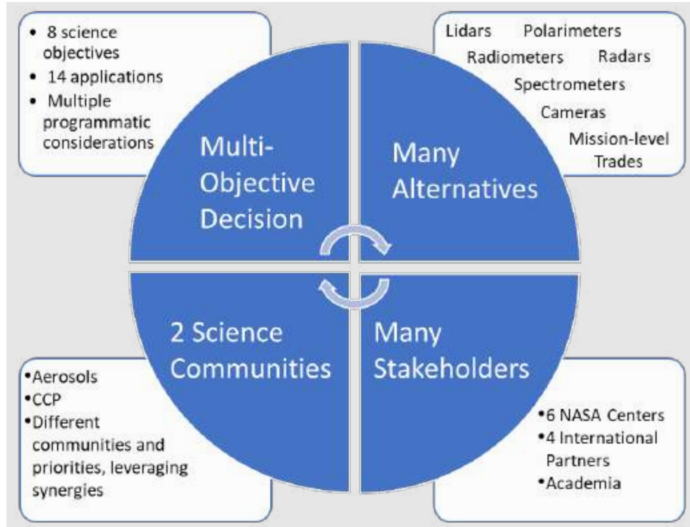


Figure 8.1: Key elements of the ACCP decision problem motivating the need for a Value Framework.

Previous approaches have been proposed at NASA to describe the Science benefit (National Academies 2015, Wielicki et al. 2016) of Earth Science mission concepts. Other high-impact work has supported the assessment of alternatives and/or prioritization of activities for NASA's other mission directorates at the organization strategic level: portfolio development for the Small Business Innovation Research program in the Space Technology Mission Directorate (NASA 2021), development and evaluation of campaigns of crewed Mars missions for the Human Exploration and Operations Mission Directorate (Goddliff et al. 2015), and frameworks for assessing aviation safety research and technology portfolios for the Aeronautics Research Mission Directorate (Jones and Reveley 2014). The ACCP Value Framework leveraged concepts from this body of work to develop an approach that can be applied to a variety of science pre-formulation activities while being tailored for the needs of the ACCP study. This approach is holistic and examines all the elements of the decision space to understand trade-offs and decision drivers, taking both technical performance and programmatic considerations into account. Ultimately, the ACCP Value Framework decomposed the complex decision problem into manageable elements, enabling a comprehensive characterization of the candidate architectures and informing the decision-making process.

Approach to Assessing Value - The Framework defines value as the relative worth of the benefits obtained from the achieved science, the benefits obtained by the enabled science applications, and the benefits obtained from certain programmatic factors, with respect to the cost and risk associated with the candidate architecture (Fig. 8.2). Each component of value was assessed over the course of the study for many of the architectures under consideration, with special emphases on consistency, objectivity, and rigorous documentation.

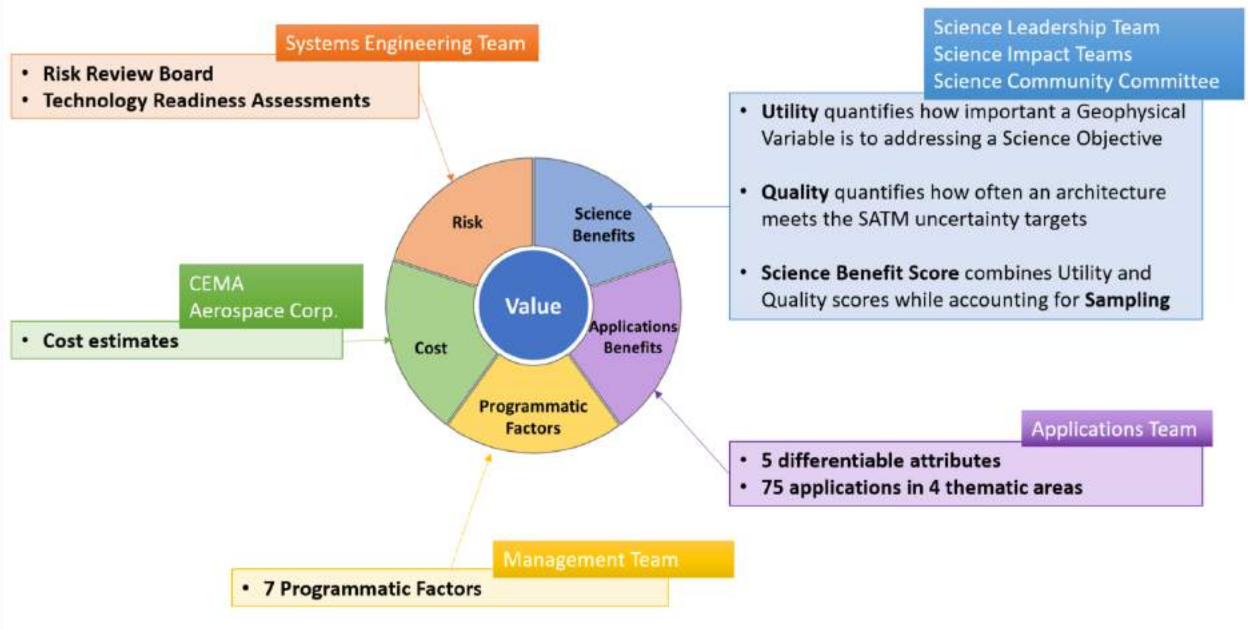


Figure 8.2: The five components of Value in the ACCP Value Framework, and key aspects of each.

The assessment of the science benefit relied on two components (Fig. 8.2): Utility and quality. Utility quantified how important a geophysical variable was to addressing a science objective. Utility was architecture-agnostic and therefore remained constant for all architectures under evaluation. The Science Leadership Team, who had collective knowledge, experience, and relevance across ACCP science topics, followed an elicitation protocol based on a modified Delphi method to quantify utility (Ivanco and Jones 2020). Quality quantified how often an architecture met the SATM uncertainty targets. Quality was architecture-dependent, and therefore varied across candidate architectures. Two Science Impact Teams, one focused on Aerosols (SIT-A) and one focused on Cloud, Convection, and Precipitation (SIT-CCP) defined approaches based on Observing System Simulation Experiments (OSSEs) to quantify quality for each architecture at the geophysical variable level. These informative OSSEs were augmented by structured expert judgment to produce representative and defensible quality scores. Utility and quality scores were combined to produce a score representative of the operational efficiency of the architectures; science benefit scores at the science objective level were then derived by accounting for sampling considerations. While aggregate benefit scores were used to summarize the assessment, the constituent scores, their sources, and their rationales were documented to maintain traceability and retain the ability to revisit the sources of the evaluation. The other components of value were assessed by the relevant teams, with tailored methods and processes.

Summarizing Value – The ACCP Team developed "Baseball Cards" (Fig. 8.3) to communicate the output of the value analysis. These summary products provide high-level information on the five components of value for each of the 3 most promising architectures. The first page includes a visual representation of the candidate architecture, some technical highlights of the instrumentation included in the concept, and science, applications, and programmatic narratives that outline pros and cons for the architecture. The second page displays the aggregated science benefit score at the science question level on a CONOPs chart to convey the evolution of the benefit over the lifetime of the mission. Quantitative data is also provided for the other components of value. In addition, high-level information is provided for possible descope options, as well as reserves. These baseball cards are included in Appendix B.

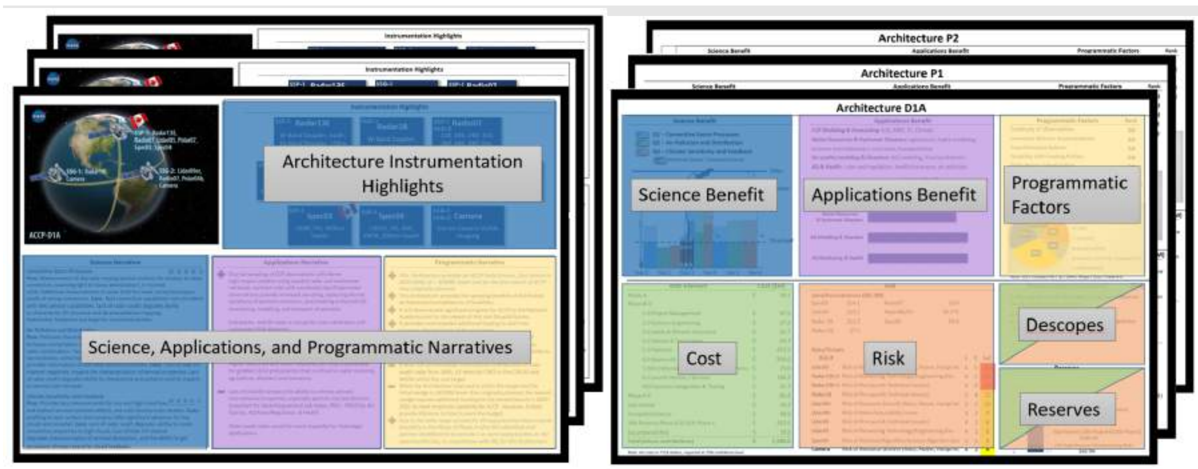


Figure 8.3: Categories of information included on the front and back of the ACCP "Baseball Cards.

8.3.2 Evaluation of quality for CCP geophysical variables

CCP Science Impact Team Methodology

The objective of the CCP Science Impact Team (CCP SIT: see Table 8.2 for membership) was to evaluate ACCP observing system architecture so that the Science and Applications Leadership Team (SALT) could make objective decisions regarding mission architecture trades. The CCP SIT delivered relative scores on measurement architectures that were derived for specific sets of geophysical variables.

At its most basic level, the CCP SIT quantified the degree to which sets of synergistic measurements with specified characteristics could provide estimates of retrieval uncertainty for geophysical quantities important to addressing science questions. The majority of the measurements and the geophysical parameters of interest are related to the microphysical properties of clouds and precipitation. Typically, the geophysical variables must be derived from measurements using radiative transfer algorithms applied through some statistical inversion methodology. The uncertainties of such retrievals depend upon measurement error, vertical and horizontal resolution of the measurements, and the degree to which sets of measurements are sensitive a geophysical variable.

In practice, the CCP SIT divided into specific Study Teams segregated by cloud types that required common methodologies to derive their properties. Then a set of quantitative results were acquired using various methods such as existing retrieval algorithms or other estimations dependent upon the observing system architecture. Once quantitative estimates were obtained the study teams met to discuss differences in the scores and also discuss how additional measurements that were not considered might improve the scores and/or how unaccounted for issues might degrade the scores. The Study Teams then agreed upon scores in light of all information. Typically, the quantitative scores were not changed by a significant amount.

The quantitative scores that the CCP SIT derived for any given geophysical variable was straightforward in interpretation. In essence, we determined what fraction of a set of representative measurement combinations could derive the target geophysical variable to within the target uncertainty listed in the SATM. Typically, only a small set of most important geophysical variables were assessed.

The types of quantitative assessment were of two broad types. One type used synthetic measurements derived from model output (Model OSSEs) and another used field program data in OSSE-like exercises (field OSSEs). Model OSSEs were used where many thousands of estimates of a geophysical variable could be derived quickly. Despite the fact that models must parameterize cloud and precipitation processes, the sheer number of cases and the diversity of model output made this method of assessment quite powerful. Field OSSEs were used in circumstances where synthetic measurement calculations were computationally intensive and only a few unique results could be calculated due to time constraints. Field Data OSSEs are advantageous, in that they involve measurements derived from real nature instead of synthetic nature (i.e., models), but suffer from a lack of diversity and adequately sampled cases. In practice, both methods were used.

Table 8.2. CCP SIT membership and affiliation.

Objective 1 and 8 Low Clouds		Objective 2 High Clouds		Objective 3 Deep Convection		Ojective 4 Cold Clouds	
Lead: Derek Posselt (JPL)		Lead: Ian Adams (GSFC)		Lead: Timothy Lang (MSFC)		Lead: Pavlos Kollias (SUNY Stonybrook)	
Matt Lebsock	JPL	Min Deng	Univ. of Colorado	Mircea Grecu	GSFC	Joe Munchak	GSFC
Rick Schulte	Colorado State Univ.	Yuli Liu	Universtiy of Utah	Pavlos Kollias	SUNY	Jay Mace	Univ. of Utah
Yuli Liu	Univ. of Utah	Joe Munchak	GSFC	Dan Cecil	MSFC		
Jay Mace	Univ. of Utah	Bastiaan Van Diedenhoven	NASA GISS	Rachel Storer	JPL		
Bastiaan Van Diedenhoven	NASA GISS		Joe Munchak	GSFC			
Dan Miller	GSFC		Ziad Hadaad	JPL			
Anthony Davis	JPL		Patrick Gatlin	MSFC			
Ian Adams	GSFC						

ACCP SIT Study Team Summaries

O1/O8 Low Clouds with elements of O4 Cold Clouds:

The ACCP SATM identifies cloud feedbacks associated with low level clouds and aerosol-related indirect effects as one of the most important problems in climate science. The critical sampling aspects for low-level clouds included extrinsic properties of detection capability near the surface where precipitation from low level clouds – especially marine low clouds – occurs and modulates the boundary layer thermodynamics. Thus, investigations of the impact of radar sampling characteristics were closely scrutinized. The analysis was based on design characteristics of various proposed radar instruments, and on the experience of the team in analyzing existing radar observing systems such as CloudSat, GPM, and RainCube. The analysis considered radar sensitivity, range bin length, and contamination by ground clutter in simulated observations of low clouds and light precipitation. The outcomes of this analysis resulted in various modifications in radar design to meet anticipated science requirements. The resulting radar designs alternate between compressed and uncompressed pulses to provide both sensitivity and near-surface capabilities.

An important aspect of sampling the properties of low-level clouds must account for their small spatial scales. The effect of partial filling of the radar and radiometer footprints were considered using output from Large Eddy Simulations (LES) precipitating shallow clouds following the approach of Lebsock and Suzuki (2016). Comparisons were then performed between the simulated observations at the radar footprint and the native LES resolution to quantify bias errors due to the finite radar footprint. The sampling uncertainty was accounted for in assessing geophysical variable uncertainty.

Quantitative assessment was accomplished using Bayesian methodologies in OSSEs (i.e., Markov Chain Monte Carlo or MCMC: Xu et al. 2019; Mace et al. 2021 – Fig. 8.4), and interrogation of large eddy simulation datasets (Fig. 8.5). The MCMC and Optimal Estimation (OE) experiments

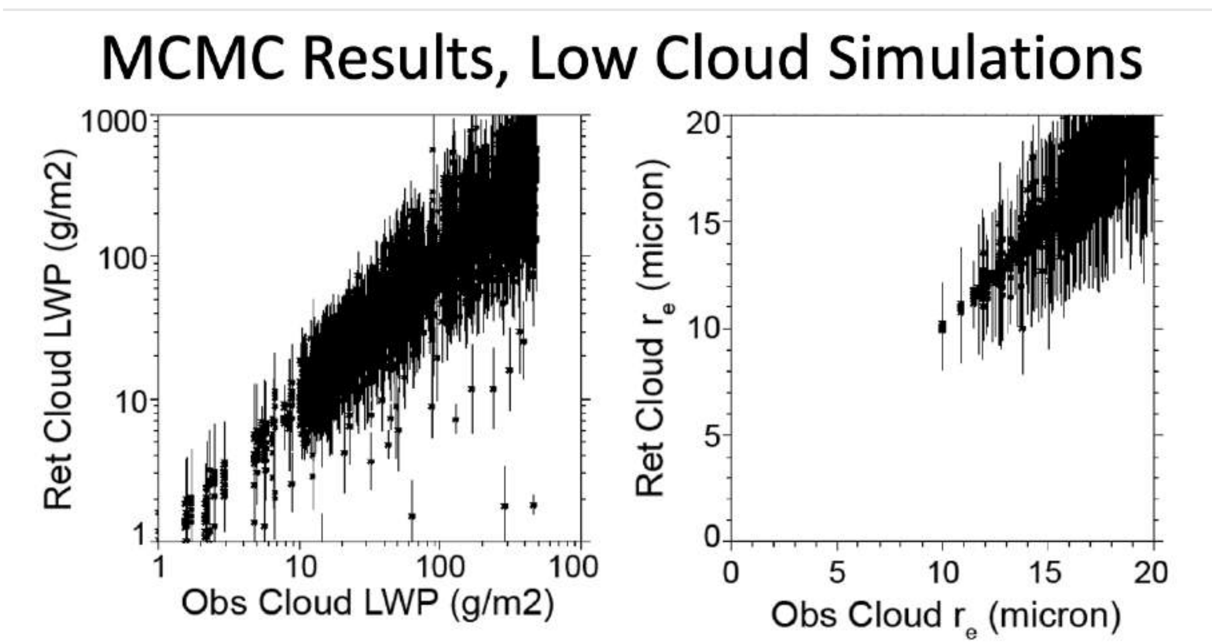


Figure 8.4. Uncertainties in (left) cloud liquid water path and (right) cloud effective radius derived using a model OSSE and a retrieval simulation using optimal estimation that includes sampling uncertainties with a database of cloud profiles derived from an LES simulation of low-level clouds. Input to this algorithm were dual frequency w- and Ka- band radar reflectivity, microwave brightness temperatures at the radar frequencies, path integrated attenuation, and visible and near IR reflectances (Mace et al., in preparation).

demonstrate that it remains a challenge to diagnose cloud properties in the presence of light rain because of the tendency of microwave remote sensing to respond to the larger droplets. Rain properties are significantly better constrained than cloud properties. The addition of Ka-band measurements places substantial constraints on the precipitation rain effective radius and rain rates. Microwave Tb offers important information regarding the column-integrated condensate mass, the measurement accuracy of which appears more likely to affect the retrievals of clouds with low liquid water path. Constraints provided by visible reflectances and/or lidar are critical for constraining the cloud droplet number concentration and cloud droplet mode effective radius.

Passive retrieval of cloud properties using reflected sunlight were evaluated also (Figs. 8.5). Such retrievals are important because they provide microphysical properties across the nadir track that are examined in detail by the active sensors. The forward and inverse OSSE used output of LES from the NASA GISS DHARMA model and then coupled with radiative transfer simulations (Miller et al. 2016, 2018). This simulator serves as a useful testbed for understanding how these retrievals are impacted by realistic cloud inhomogeneity and the consequences of design and observation conditions.

Precipitation rate profiles, cloud liquid water path, and total water path were evaluated using a unique Bayesian methodology (Shulte 2021). This method was based on taking rain drop size distributions with rain rates less than or equal to 2 mm/h from the OceanRAIN dataset (Klepp 2015), adding plausible profiles of cloud water and water vapor, and then using a combination of the Quickbeam radar simulator (Haynes et al. 2007) and the MonoRTM radiatve transfer model (Clough et al. 2005) to simulate multi-sensor observations of the scene. Noise was added to the simulated observations before using an optimal estimation algorithm to retrieve back the precipitate rate, cloud liquid water path, and total water path.

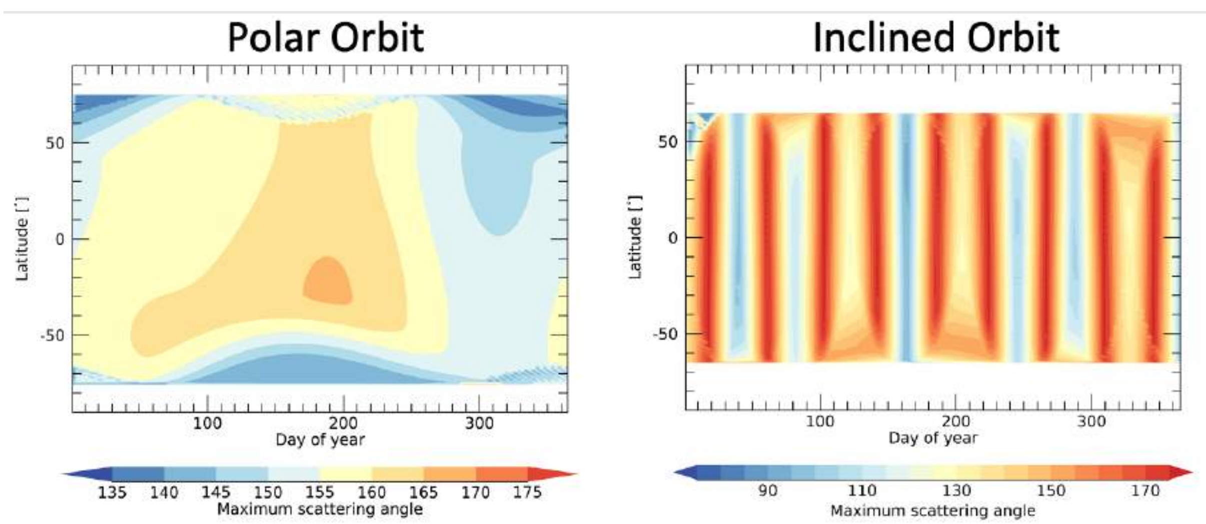


Figure 8.5. Maximum scattering angles available for use in polarimetry measurements for (left) polar and (right) inclined orbits. The maximum available information is obtained where the maximum scattering angle is large. These results were used to scale the polarimetry informed GV scores to account for sampling. Figure Courtesy Sebastian Van Diedenhoven (Columbia University and NASA GISS).

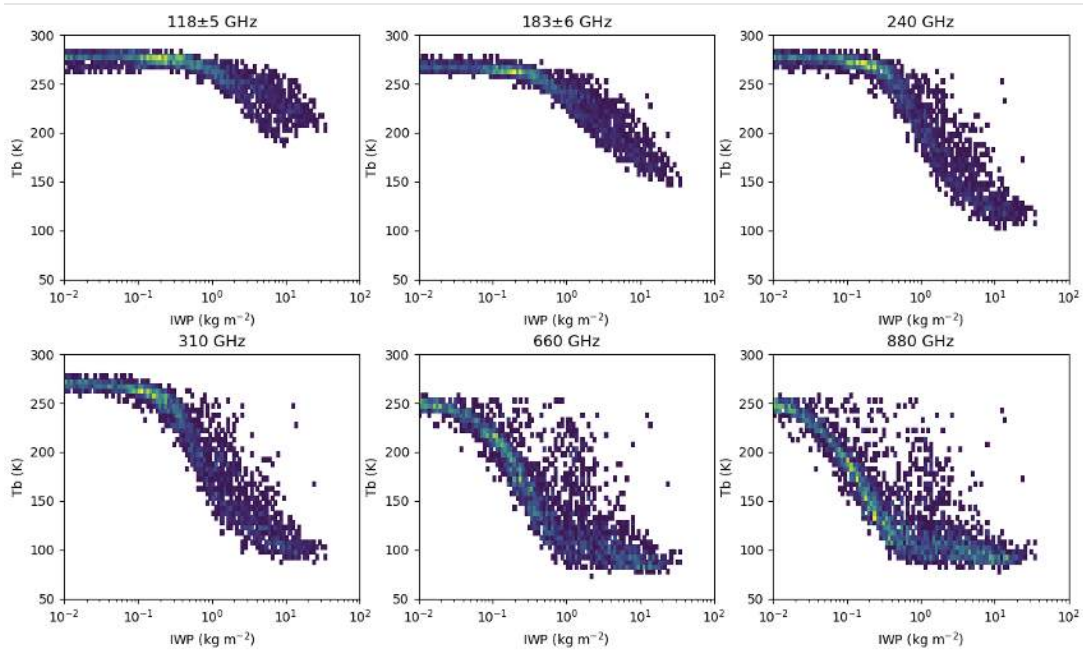


Figure 8.6. Brightness Temperature-Ice Water Path density plots for selected frequencies covering the range considered in ACCP candidate architectures. The wide dynamic range of IWP necessitates a wide range of frequencies reaching into the sub-mm range (> 600 GHz) to achieve ACCP objectives regarding high cloud feedback. Figure provided courtesy of S. Joe Munchak (NASA GSFC, Munchak et al. 2020).

O2 High Clouds with elements of O4 Cold Clouds

The High Clouds objective in ACCP is focused on the need for the ACCP observing system to characterize the properties of upper tropospheric ice clouds. These clouds are expected to have a positive feedback on the climate system in the coming decades (Zelinka and Hartmann 2010). The important aspects of the problem are to understand the injection of ice from deep convective systems to also understand how ice and water vapor spread laterally and evolve into cirrus clouds that cover much of the tropics and tend to warm the climate system (Stephens and Webster 1984).

We evaluated several microwave and sub-mm radiometer options that were selected for the candidate architectures. These included conical and cross-track scanners with frequencies ranging from 89 to 880 GHz (Fig. 8.6). These instruments were intended to provide additional constraints to the radars and lidars and provide spatial context for the narrow-swath active measurements.

Several methodologies were employed to evaluate the observing systems that included multiple-frequency radars with W-, Ka-, and Ku-band channels and a submillimeter-wave radiometer. A hybrid set of Bayesian retrieval algorithms were developed and used to assess the capability of the observing systems in retrieving ice cloud microphysics (Liu et al. 2020). In addition, optimal estimation and MCMC algorithms were employed to statistically investigate observing system capabilities. Results demonstrated that the effective Ka- or Ku-band observations, when combined with W-Band, improve the pixel-level retrieval accuracies compared to retrievals with a single W-band channel. The combined radar and radiometer retrieval results demonstrate that synergies between the active and passive observations significantly improve the retrieval accuracies of ice water path.

In addition, we used the 2C-ICE retrieval developed for A-Train that combines millimeter radar and lidar to derive cirrus properties (Deng et al. 2015) to evaluate the sensitivity of thin cirrus retrievals to the measurement architectures. We were also able to provide a rough simulation of HSRL with CALIPSO noise data and 2C-ICE cloud properties to test the benefit of HSRL on cirrus lidar-radar synergistic cirrus retrievals. We were also able to use the 2C-ICE algorithm to test the impact of sensitivity of the proposed ACCP cloud radar.

The findings from the O2 Study Team includes the following:

1) High clouds science requires the lidar and polarimeter in addition to CCP sensors.
2) Radiometer bands from 89 GHz to 880 GHz are useful for constraining ice water path retrievals, spanning the range from thick anvil clouds near convective cores to cirrus clouds down to roughly 10 g m^{-2}.
3) Backscatter-only lidar is sufficient to meet the specified requirements for high clouds, but HSRL may provide additional reductions in uncertainty.
4) W-band radars with –25 dBZ of sensitivity or better are needed for high clouds science, and Doppler capabilities at W band greatly expand our ability to perform high clouds science.
5) The polarimeter is important for cloud-top microphysics; however, some of the polarimeter capabilities are reduced in an inclined orbit due to less-than-favorable sun angles for cloud bow retrievals.

O3 Convection
The Objective 3 (O3) Convective Storms Study Team provided critical information for the transformative Doppler velocity measurement that is so fundamental to ACCP science goals. The Convection Study Team addressed challenges related to what truly represents success for a simulated measurement or simulated retrievals; e.g., what is the appropriate weighting between weak convection cases that are numerous compared to strong convection cases that are rarer but individually more impactful; what is an acceptable error bar for strong vertical motions; and how do we score an observing system that gives small errors but often fails to make certain measurements, versus one that gives larger errors but more complete measurements. The O3 team determined that architecture performance in deep/intense convection should be weighted strongly in the scoring process, due to the disproportionately large effect of strong convection on the global water and energy cycles (e.g., Boccippio et al. 2005, Liu et al. 2008). Thus, the O3 team was able to make a quantitative case for including Ku-band Doppler radar in each of the final three architectures. An example of the O3 scoring approach is shown in Fig. 8.7.

Other O3 precipitation-related GVs were assessed using a synergistic Bayesian methodology developed for GPM (Grecu et al. 2016). To deal with Ka-band reflectivity observations that are severely attenuated, a statistical regularization technique was developed. An illustration of the concept in shown in Fig. 8.8.

8.3.3 Evaluation of quality for A geophysical variables
The Science Impact Team A (SIT-A) was charged with quantitatively evaluating retrieval uncertainties for aerosol-related Geophysical Variables, comparing them to SATM requirements, and translating these comparisons into Quality Scores that could be used in the Value Framework.

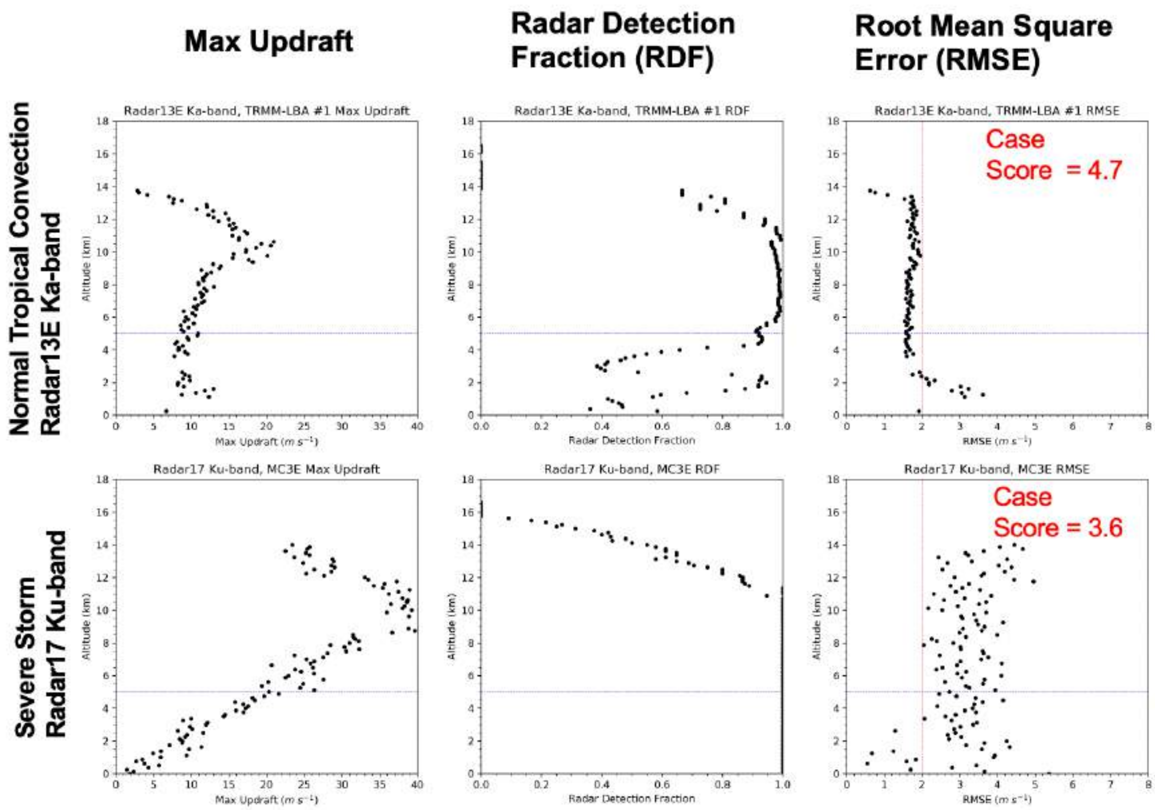


Figure 8.7. Example of how the IVAV.z scoring system worked in O3. Retrievals were performed for various radar systems across multiple canonical cases studies, which included everything from weak, shallow convection to intense mesoscale convective systems (MCSs). Maximum updraft (left) at each altitude level was considered, as were radar detection fraction (RDF; center) and root mean square error (RMSE; right). The acceptable uncertainty limit at most levels was 2 m s^{-1}, but this limit was increased when maximum updraft was large (> 6 m s^{-1}). Radars that had high RDF and low retrieval errors for a case (e.g., top panels with Radar 13E —W, Ka band DPCA Doppler— sampling ordinary tropical convection) received a high score for that case (maximum possible was 5), while radars that had higher errors for a particular case (e.g., bottom panels with Radar 17 —Ku Doppler radar with swath— sampling a severe MCS) received a more modest score. The final score for each radar was a weighted combination of its scores for all cases.

This process was intended to highlight relative performance differences among various instruments and instrument combinations that could be used to retrieve the GVs.

The SIT-A consisted of representatives from all NASA centers involved in the study and various University partners, with actual aerosol retrieval algorithm development taking place at GSFC, LaRC, GISS, the University of Oklahoma, and a team of French partners led by researchers at the LISA (Laboratoire Interuniversitaire des Systèmes Atmosphériques, at the Paris-Est Créteil University). The SIT-A was aided by the Lidar Working Group (LWG, comprised of representatives from the University of Wisconsin, LaRC, and GSFC), which was focused on lidar performance and design requirements, while the SIT-A was concerned primarily with aerosol level-2 retrievals from lidars, polarimeters, or their combinations.

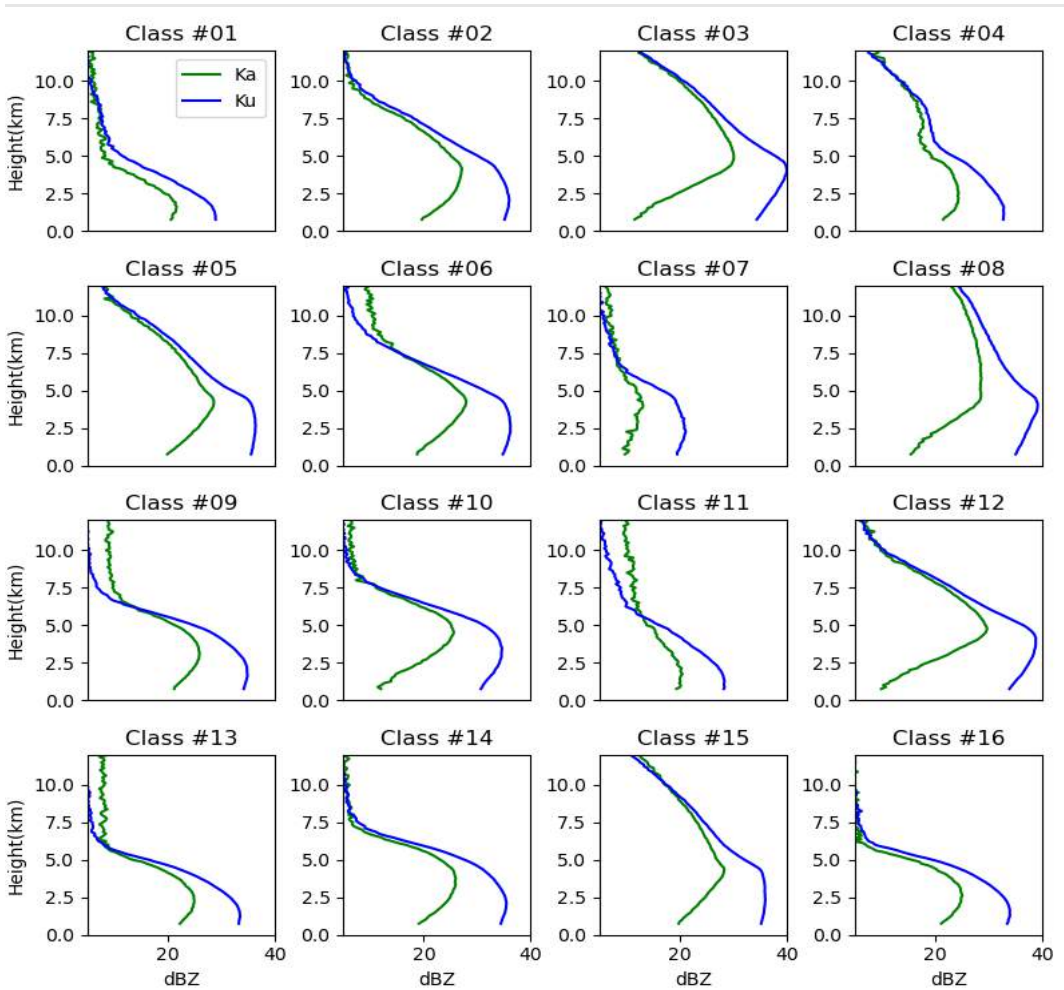


Figure 8.8. Classes of Ka-band reflectivity profiles derived using a k-Means clustering approach. Figure courtesy of Mircea Grecu (Morgan State University, NASA GSFC).

The functional definition for Quality Scores (QS) for a given GV is the fraction of retrievals that provided uncertainties or errors within the requirements specified in the SATM. Four primary methods were employed to assess retrieval uncertainties and errors:

- Information Content Analysis (ICA), using a retrieval-free methodology to determine the basic sensitivities of the measurements independent of retrieval assumptions and constraints (Burton et al., 2016);
- Statistical Direct Retrieval Simulations (DRS), using canonical aerosol cases or nature run output to retrieve GVs from simulated, noise-added signals;
- Statistical Performance Analysis (SPA), using a broader set of aerosol properties, and a forward model with optimal estimation in a coupled (atmosphere-ocean) retrieval;
- Real Data Analysis (RDA), using actual suborbital data collected by lidars and polarimeters to test retrievals (Xu et al., 2021).

All four retrieval methodologies were supported by lidar uncertainty analyses carried out by a team of researchers from LaRC and GSFC. Some of these methodologies were employed by multiple SIT-A participants, and none of the groups were solely focused on any one approach. The advantage of this approach is the comparability of results derived from the same methodologies by different groups. In this manner, the SIT-A learned both about the instrument capabilities and about the strength and weaknesses of the retrieval methodologies in the context of specific GVs.

Retrieval conditions were varied for different observing modes (i.e., Nadir vs off-nadir, day-time vs. night-time), for different surface types (i.e., ocean, dark land, bright land), for a set of 30 canonical aerosol cases (i.e., each case constructed from four aerosol types with different loadings, vertical distributions, and microphysics), for clear skies and below an example Cirrus cloud with OD=0.5. These conditions were applied to three different lidars (lidar 5 – HSRL-1; Lidar 6 – HSRL-2; lidar 9 – backscatter lidar) and two polarimeters (polarimeter 4b and 7 of the RFI tables provided). For a given GV, retrieval QS from some of the permutations were aggregated into mean QS to reflect approximately the relative global frequency of occurrence of these conditions.

In a secondary evaluation step, the SIT-A Study Team, i.e., a group of 13 lidar and polarimeter experts from among the SIT-A, assessed the physical plausibility of retrieval simulation results. For instance, results were flagged for further investigation if the retrieval assessment indicated instrument-to-instrument differences that were implausible based on physical principles, likely measurement information content, and recognized weaknesses of the assessment methodologies. In accordance with direction from the leadership team, the Study Team adjustments were "light-touch". Averaged over all aerosol GVs, Study Team absolute adjustments to mean QS were about 0.03. Mean adjusted QS were reported to the Value Framework team as required, organized by retrieval conditions specified in the SATM (e.g., day-time vs night-time), for subsequent weighting by conditions for each objective in the SATM.

Overall, the complementary retrieval methodologies provided physically plausible and significant differences in retrieval capabilities between instruments and instrument combinations. For the joint lidar+polarimeter retrievals that have been viewed by many as the most significant advancement within the ACCP observing system, the QS for polarimeter+lidar-6 were about 0.1 greater than the QS for polarimeter+lidar-5. In turn, the QS for polarimeter+lidar-5 were about 0.2 greater than the QS for polarimeter+lidar-9. The SIT-A considers these differences significant, in that they can mean the difference between meeting and not meeting threshold science requirements for the ACCP mission as a whole. Journal publication describing the various individual retrieval assessment methodologies and a separate publication discussing how the SIT-A combined them to produce QS are currently being developed.

Limitations to the SIT-A assessments were noted with respect to some of the absorption-related aerosol GVs, and possibly others, in that some of the joint lidar+polarimeter assessment methodologies continued to produce physically implausible similarities between the observing systems featuring different lidars. This can be due to (i) the joint retrievals placing undue emphasis on polarimeter information content (via smoothness constraints on particle microphysics); (ii) retrieval constraints imposed on the imaginary index of refraction and its spectral dependence artificially enhancing the retrieval capability of all instrument combinations; (iii) particle typing capabilities that were implicitly assumed to provide additional constraints to the joint retrievals (via refractive index and size constraints) having different impacts on the individual teams' QS; (iv) different joint retrieval methodologies using different assumptions regarding how to deal with non-convergent cases; and (v) the number of cases run per simulation setup being insufficient to produce a statistically converged result. By design, the various assessment methodologies had different strengths and weaknesses, and in this case, the ICA methodology is subject to fewer of these limitations that impact the absorption-related GVs, and so the ICA results provided perspective that was useful in the Study Team adjustment phase.

Besides the primary retrieval capability assessments, the SIT-A has produced a number of additional notable outcomes: the LWG confirmed the feasibility of spaceborne HSRL observations; the retrieval development work at the various participating institutions produced retrieval capabilities far beyond any of those published previously, and these capabilities were tested in a broader set of conditions than any previous assessments; and our French partners demonstrated notable differences in particle typing capabilities among the different lidar concepts.

As described in the SIT presentations at the NASA HQ review in February 2021, the aerosol algorithms being developed by the SIT teams are key to the synergistic observations of ACCP. This synergism exists between different instrument combinations (e.g., lidar+polarimeter, radar+radiometer), but also between aerosol and cloud retrievals in joint scenes. The success of both aerosol and cloud retrievals will greatly depend on the continued development of these coupled retrievals, an undertaking that needs to be expanded well beyond the scope of what the SITs were able to do in the ACCP DO study to date. The framework for such retrieval development has been created; it takes the form of a highly collaborative, inclusive SIT-A retrieval community, coalesced around results that are well understood, yet need to be enhanced continuously in the mission design phase.

8.3.4 Evaluation of applications benefit

The approach to scoring of the ACCP architectures from an applications perspective took many forms before the final scoring implementation due to the complexities of the potential instrument suites as well as the diverse set of factors that would enhance applications benefit. Through direct engagements with stakeholders via workshops, interviews, and other conversations as well as leveraging the Applications Impact Team's (AIT) expertise, the team identified 75 potential enabled applications and then downselected to 12 enabled application areas on which the ACCP measurements would have high impact. These areas cut across CCP Modeling & Forecasting, Water Resources & Hydrometeorological Disasters, AQ Modeling & Disasters, and AQ Monitoring & Health (Fig. 8.9).

Defining Scoring Attributes: For each of the enabled applications areas, we considered a series of attributes based on instrument characteristics (e.g., resolution, swath width), architecture characteristics (e.g., orbit), and measurement characteristics (e.g., latency, accuracy). While all attributes were generally considered during previous scoring exercises and during the evaluation process, five specific considerations formed the basis for the final scoring. The three specific attributes considered for scoring are shown in Fig. 8.10.

Thematic Divisions	Enabled Applications
CCP Modeling & Forecasting	S2S (Applied Research)
	NWP (Applied Research)
	Climate Modeling (Applied Research)
	Aviation (Operational Decision Support)
	TC forecasting (Operational Decision Support)
Water Resources & Hydromet Disasters	Hydrologic Modeling/Water Resources/Agriculture (Decision Support/Policy Planning)
	Hydrometerological Disaster modeling (floods, landslides), Insurance (Decision Support/Policy Planning)
AQ Modeling & Disasters	Disasters - Aerosols (Volcanic plumes, dust storms, large wildfire events)
	Air Quality Modeling (forecasting)
AQ Monitoring & Health	Human Health (aerosols)
	AQ Rule and Regulation Making
	Air Pollution/Air Quality monitoring

Figure 8.9. Applications Thematic divisions and the specific enabled applications within each category used for scoring ACCP candidate architectures.

Under measurement characteristics, we refer to continuity and novelty. We define the differences between these terms as follows. *Continuity* measures the ability of a given suite of instruments, or architecture, to provide products that are currently provided by other PoR missions and that the Applications community relies on in a sustainable way to provide products for societal benefit. *Novelty* measures of ability of the proposed improvements in instrument suite, instrument capabilities, and/or orbit to improve data (above PoR) for current applications and/or enable new applications and stakeholder groups (i.e., "raises the bar").

Final Scoring Approach: The AIT then convened according to expertise in A and CCP applications and assigned applications benefit scores for each of the 15 final proposed architectures from a score of 0-1 (not relevant to the applications area) to 5 (very high applications value). A 0-5 score was assigned for each application area and results were averaged by architecture across each Thematic Division to provide 4 scores, 2 CCP- and 2 Aerosol-based, for each architecture. These results were then incorporated into the "baseball cards" for each of the final 3 architectures (Fig. 8.11). The scoring was accompanied by a narrative to highlight the most significant areas of applications value and also identify potential areas for further enabling applications. These results were first shared with the Study Leadership team and later with NASA HQ and other technical teams.

Lessons learned from Applications Scoring for ACCP: The first time the applications-based architecture scoring was presented, it became clear that the applications benefit can differ significantly in some cases based on stakeholder needs. For example, it was a challenge to figure out how to consider and score continuity versus novelty. Some user communities rely on a long and consistent record of a measurement, such as precipitation for parametric insurance modeling, and as a result continuity of measurements is vital to maintain and advance their applications. For other communities such as air quality monitoring groups, the novelty of ACCP measurements to resolve vertical distribution of aerosols is of high applications benefit. As a result, the AIT needed to be careful and purposeful in how enabled applications and their stakeholder communities were

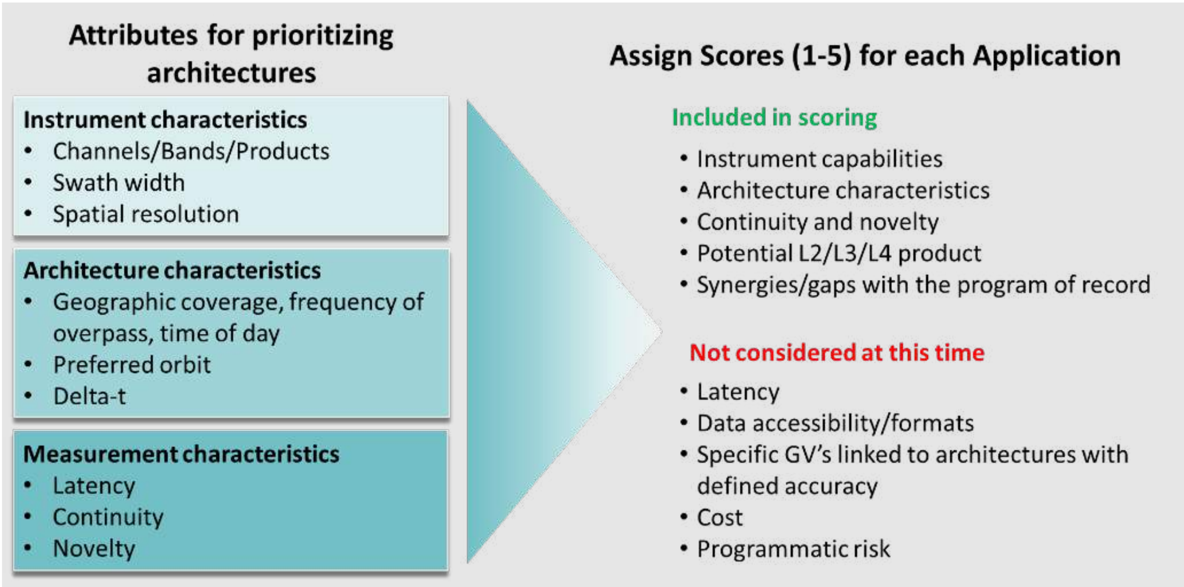
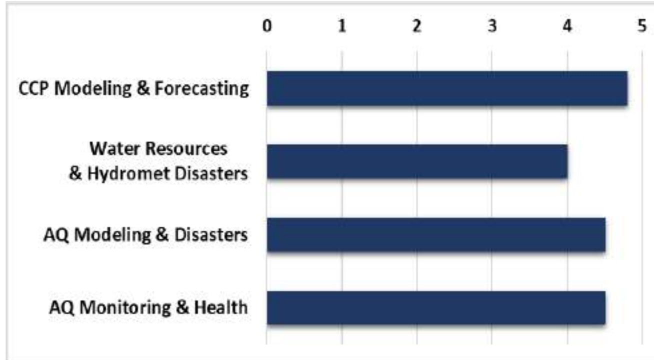


Figure 8.10. The left boxes highlight the attributes considered as important for applications communities and the right section lists those topics that were considered during the scoring process for each enabled application and architecture.

represented so as to best highlight the specific applications value and benefits for a particular architecture and instrument suite.

The first opportunity for scoring provided insight into how the study team perceived the assessments and how to communicate them, e.g., such as when the team scored an instrument high or low based on the applications criteria and stakeholder needs. As an example, some of the radar options scored low for many application areas because of the narrow swath and the knowledge that at present, this would be of limited utility to applications communities today; however, the novelty of these measurements may provide benefit in the future as new communities are able to exploit this type of information. Many of the early attempts at assigning applications benefit were based on limited instrument information without knowledge of measurement quality, temporal resolution, or orbit. As the study progressed and architecture information became more tangible, the AIT was able to narrow the applications down to the 12 shown in Fig. 8.9 and to identify the most relevant ones to directly address scoring and identify gaps in architecture options. This included requesting the possibility of a lower-frequency radiometer channel (near 89 GHz), the importance of an inclined orbit for many applications areas, and the aerosol limb imager (ALI) for air quality estimation and constraining other instrument measurements. Ultimately, the team learned that creating an objective numerical score was a difficult task. The AIT could best convey applications benefit through qualitative scoring and supporting narratives that included stakeholder input and feedback. In the process, it was essential to have continued discussion between the SALT, SIT, SET, and AIT. Reliance on other teams was important to connect the developing ACCP capabilities to applications. While most of the AIT is familiar with a particular instrument or channel, tapping into the depth of knowledge of instrument experts was important to further translating the science to potential applications.

8.4 Input From The Scientific Community Committee



Overall Statement: The architecture provides the most opportunity for enhancing and extending applications for both aerosols and CCP. The diurnal sampling made possible by the inclined orbit is fundamental for improving extreme event forecasting, advancing climate modeling, and enhancing air quality monitoring and modeling. The combination of instruments in an inclined and polar orbit along with the program of record will be game changing for climate model parameterization, air quality modeling and transport of aerosols, and severe storm forecasting.

Figure 8.11. Example of scoring for each architecture presented in the study summary. This was accompanied by an overarching statement.

The Scientific Community Committee (SCC) was an independent committee comprised of university faculty and non-NASA laboratory mid-career scientists with expertise in aerosols, convection, clouds and precipitation. By design, the SCC members therefore represented the broader science community and end users of the ACCP observations and associated datasets. The SCC worked intimately with both the Science and Applications Leadership Team (SALT) and the Science Management Team (SMT), and as such, fulfilled two primary roles: (1) **assisted** in the development of the scientific goals and approaches of the study; and (2) **assessed** whether the needs of the broader scientific community were being met through the proposed goals and approaches. More specifically, the SCC contributions to the study included feedbacks and commentary on: the science objectives and overarching statements; proposed methodology; proposed instruments; proposed architectures; proposed applications; and the narrative. A number of members of the SCC were also actively involved in the Modeling, Suborbital and Radiation working groups. The SCC conducted its work throughout the study via routine group conference calls, frequent science objective subcommittee calls, face-to-face meetings, and participation in the ACCP SATM and Architecture Evaluation workshops. The SCC presented its findings and feedback to the SMT and SALT at full team ACCP workshops and briefings.

The SCC's primary focus was on the science opportunities offered by a new mission, and it deliberated on what observations would enable further advances in key science questions related to aerosols, clouds, convection and precipitation. Measurements of in-cloud vertical velocities and the vertical distributions of aerosol properties were identified as transformative elements of ACCP. The committee also identified the importance of improving our understanding of atmospheric processes through coincident measurements of aerosol, cloud and radiation (microphysical and dynamical) parameters and by observations separated by a small difference in time (e.g., seconds to minutes), referred to as Delta-t sampling. The importance of measurements at different times of the day to advance the understanding of convective processes and their evolution, as well as biomass burning emissions, were also articulated by the SCC.

The SCC concluded that 5 remarkable "FIRST-EVERS" will be achieved by ACCP:

1. Global Observations of Vertical Motions at Cloud-Scale via Doppler Radar

2. Global Observations of Vertical Distribution of Aerosol Size, Absorption, and Extinction via HSRL Lidar
3. Collocated Dynamics, Microphysics, Aerosol and Radiation Observations
4. Cloud and Aerosol Processes through Delta-t Observations via Stereo Cameras
5. Diurnal Cycle Cloud and Aerosol Observations via an inclined orbit

These novel, transformative measurements will not only enhance our understanding of the earth's weather and climate system, but will also allow us to better predict cloud and aerosol processes on weather through climate scales. Details of the Doppler Radar, HSRL Lidar and stereo camera instruments are presented in sections 7.1, 7.3, and 7.6.1, respectively.

The SCC also discussed the importance of the sub-orbital component of ACCP and recognized that both airborne and surface observations are critical elements to ensuring the success of the proposed mission. The sub-orbital component, along with further development of the modeling component of ACCP, are needed to advance the approaches to be applied in using ACCP observations to meet the science objectives of ACCP, and include aspects ranging from OSSEs and data sufficiency before mission launch through to ground-validation post launch.

Finally, the SCC provided feedback on the evolving selection of proposed architectures throughout the study, as well as the final architecture selections. The findings of the SCC regarding the three final architectures were in strong support of the SALT, SIT and SMT recommendations. Following an independent SCC poll it was shown that 80% of the SCC identified D1A as their top priority, while 10% chose P1 as their top priority, and the remaining 10% chose P2 as their top priority. D1A was identified as the top priority of the majority of the SCC primarily because of its balance in meeting the ACCP proposed study objectives. Most of the SCC believe that D1A will be successful in delivering ACCP's 5 FIRST EVERS.

9. ACCP Final Architecture Options

9.1 Prioritization of Architectures

9.1.1 Integration of insights from the quality assessments

Based on the work of the SIT and Value Framework teams, the ACCP team had a wealth of valuable quantitative information on a number of architectures. They ultimately needed a means to use that information to narrow down to three final architectures. Here we describe how the team used the insights gained from the science benefit scoring to identify the priorities for three of the most important DS science questions (questions W-4, W-5, and C-2 in Table 3.1) and a set of "Balanced Architectures".

First, we summarize the evolution of the scoring process (Fig. 9-1) and some of the insights gained from the value framework evaluation. After the development of a reasonably mature SATM by spring 2019, the study team developed a large number of architectures at the ACWs (section 8.2.3). After each ACW, the SALT would do a qualitative evaluation of the science benefit as more quantitative assessment capabilities were being developed. The qualitative assessments were primarily based on previous experience with measurements from space-borne or airborne instruments and capabilities. The final qualitative assessment was joint with the SCC in Dec. 2019.

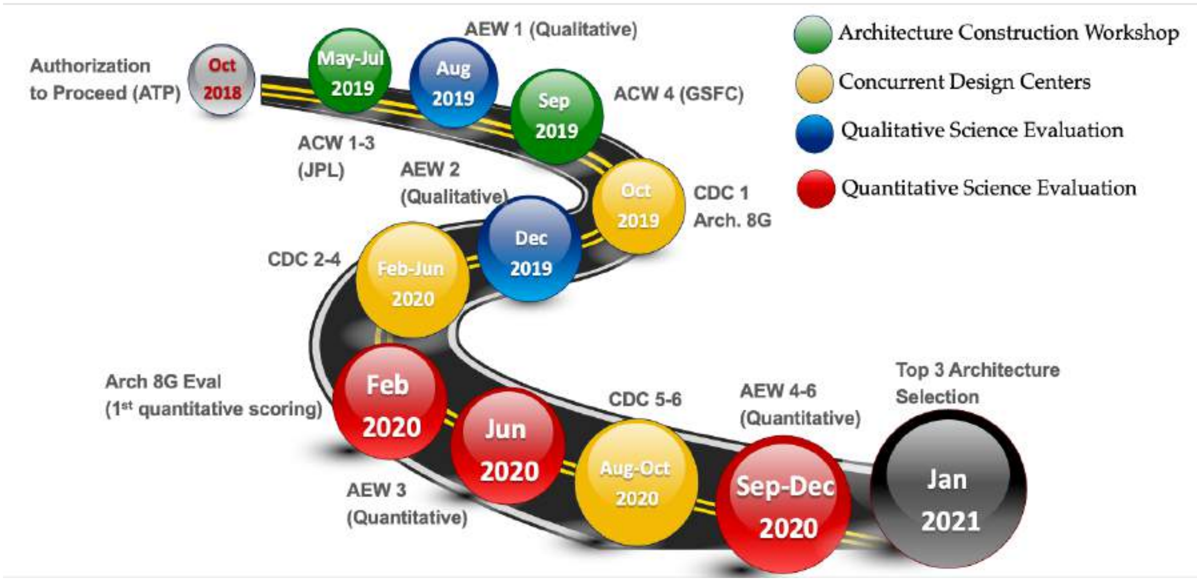


Figure 9-1. General roadmap of the architecture design and evaluation process that led to the final architecture selection.

Starting in early 2020, the SIT teams were able to present their first comprehensive quantitative assessments that were gradually refined as the team continued to explore and fine tune additional architectures using the CDCs. These quantitative SIT assessments sometimes demonstrated shortcomings for some of the measurement approaches that then led to appropriate refinements of the instruments that became part of the final architectures.

Next, we discuss some of the key findings related to the active instruments, particularly since they are in many ways the key drivers of the architectures in terms of both science and cost. The W-band radar, known as a cloud radar, is capable of measuring clouds and light precipitation. Because ACCP has a significant interest in profiling low clouds as part of the climate DS science question, a radar capable of profiling close to surface is needed. While some sensitivity is lost relative to CloudSat (minimum detectable reflectivity above the surface clutter zone of –25 dBZ versus –30 dBZ for CloudSat), we obtain a radar capable of measuring profiles of drizzle down to a few hundred meters above the surface while CloudSat might only see cloud top for shallow low clouds. This capability will be needed not only for low clouds, but also for measuring snow to near the surface where phase transitions can often occur and be missed by other radars like CloudSat and GPM.

Ka and Ku-band radars are better suited to moderate and heavy precipitation and are particularly needed for convective storms. For a typical convective system, the cloud radar can't penetrate very far into the region of heavy rainfall. Penetration improves for Ka band, while Ku band often penetrates to the surface. For Doppler measurements, dual-antenna techniques such as the displaced phase center antenna (DPCA) approach are expected to significantly improve Doppler quality and avoid some of the errors associated with single-antenna approaches. The JAXA radar is the only solution available in the study for the wide-swath measurements desired for applications.

The activities of a Lidar Working Group and the aerosol SIT team led to key insights about the lidars. The backscatter lidar offers significant SNR improvement relative to CALIPSO, but because it measures only the total backscatter, one must make assumptions about the lidar ratio to separate out the molecular and particulate components, leading to errors in retrieved properties. Moving from the 2-channel backscatter lidar to a lidar with 1 HSRL and one backscatter channel leads to significant improvement in terms of SNR, optical depth estimates, and retrievals of aerosol properties. The addition of a UV HSRL channel provides a clear advantage for better identifying aerosol types and further improvement of retrievals of aerosol properties.

For the remaining instruments, using the qualitative and quantitative benefit scoring, we were able to identify key lessons related to necessary capabilities, resolution, channels, their value as critical retrieval constraints, and new science. Passive microwave radiometers are essential for context and for constraints on precipitation and cloud ice properties. Desired capabilities include convection-resolving resolution and an 89-GHz channel for precipitation measurements. The team examined time-differenced passive microwave measurements and found that they are likely useful, but retrievals from this approach are at a low maturity level. Polarimeters provide essential constraints for aerosol retrievals and higher spatial resolution is generally preferred over a wider swath (the trades included half the resolution for double the swath width). Spectrometers are essential for radiation measurements collocated with clouds and aerosols and also provide information on cloud and aerosol properties that are complimentary to the lidars and polarimeters. Stereo cameras provide innovative measurements of cloud and aerosol plume dynamics and were identified as the highest priority among the different types of time-differenced measurements. The concept is reasonably mature with clear deliverables. Finally, limb aerosol and moisture sounders (contributed instruments not described in section 7) provide valuable information on upper tropospheric/lower stratospheric aerosols and moisture.

9.1.2 Science and instrument prioritizations

Common building blocks

In the course of exploring nearly 100 architectures, a set of core capabilities emerged that were common to many of the top-scoring architectures. We refer to these capabilities as common building blocks. In polar orbit, the building block included

- A cloud and precipitation profiling radar (W- and Ka-band frequencies) that uses the DPCA approach for Doppler velocity measurements at both frequencies and capable of profiling to within a few hundred meters of the surface
- An HSRL lidar (HSRL at 532 nm and backscatter at 1064 nm) with excellent SNR and high vertical resolution for more accurate aerosol and cloud profiling
- A passive microwave radiometer with a minimum set of frequencies ranging from 118 to 880 GHz
- A multi-angle, multi-frequency polarimeter with high spatial resolution for cloud and aerosol properties and strong constraints on lidar retrievals
- A pair of spectrometers spanning frequencies from ultraviolet to far infrared for estimates of radiative fluxes associated with clouds and aerosols

A number of architectures consisted of dual-orbit solutions, with a set of very capable instruments in polar orbit and a set of sometimes less capable instruments in an inclined orbit to provide information on diurnal variability. Some architectures focused only on CCP-related objectives, recognizing that diurnal variability is critical to studying convective processes. Other architectures, though, struck a balance between aerosol and CCP science. The SIT evaluations showed quite clearly that the highest benefit scores were associated with inclined architectures that addressed the full set of ACCP objectives, and as a result, dual-orbit solutions also contained a common set of building blocks. In the inclined orbit, the common building block included

- A cloud and precipitation profiling radar (W- and Ka-band frequencies) that uses the DPCA approach for Ka band
- A passive microwave radiometer identical to that in polar orbit
- A backscatter lidar with frequencies at 532 and 1064 nm
- A polarimeter with half the resolution but twice the swath width as in the polar orbit

The above common building blocks in both polar and inclined orbits represent the minimum set of instrument capabilities that provide the foundation for developing single- and dual-orbit architectures. Using lessons learned about the various instrument capabilities and science benefits, the ACCP team was able to construct optimal architectures by adding prioritized augmentations of the common building blocks for each of the Decadal Survey science questions (climate, convection, and aerosols) and then formulate balanced solutions to address all three questions.

Climate question priorities

For the climate sensitivity and feedback (or forcing) question, key objectives relate to low and high clouds, cold clouds, and aerosol direct and indirect effects. For a single, polar-orbiting architecture, the greatest science benefit was expected to come from the addition of the UV channel on the lidar, which would improve identification of aerosol type and aerosol properties and improve capabilities for clouds. Next, to characterize high clouds in the context of parent convective systems, a Ku-band capability was emphasized to best measure vertical air motions and precipitation properties in areas where W- and Ka-band radars would likely fully attenuate. Tandem stereo cameras were the third priority, providing innovative information on the structure and dynamics of low clouds and aerosol plumes. Finally, aerosol and humidity limb imagers were added to relate high clouds and convection, as well as extreme aerosol events (e.g., volcanic eruptions, pyrocumulus), to upper tropospheric/lower stratospheric (UTLS) aerosols and moisture.

For the inclined orbit, given the importance of the diurnal cycle of convection, the Ku-band radar capability was given greatest priority as an add-on for this orbit. It was followed by the addition of the UV channel of the lidar in polar orbit. Because of the importance of cloud and aerosol radiative effects to the climate question, the addition of a spectrometer to the inclined orbit was of the next highest priority followed by the humidity and aerosol limb imagers.

Convection question priorities

For the Decadal Survey question related to convection, the prioritization of added capabilities was identical for both the polar and inclined orbits. Because of the heavy precipitation that can occur in deep convection and the inability of W- and Ka-band frequency radars to penetrate it, the Ku-band frequency radar was given highest priority so that vertical motions and rainfall can be profiled throughout the troposphere. The second priority was an upgrade of the passive microwave radiometer to get measurement fields of view at very high spatial resolution more commensurate with the scale of convective towers. The third priority was a pair of passive microwave radiometers flying in formation just 1-2 minutes apart to measure time rates of change in cloud and precipitation structure that could speak to the cloud microphysical processes active within growing convection. Next was the time-differenced tandem stereo cameras to provide information on the dynamics of shallow convection and potentially at the tops of deep convective storms. The final component was the humidity limb imager for measuring UTLS moisture near the tops of convective storms.

Aerosol question priorities

As with convection, the prioritized augmentations for the Decadal Survey aerosol science question were the same for both the polar and inclined orbits. Top priority was clearly the UV channel of the lidar in polar orbit because of the added value for aerosol type identification and improved aerosol property retrievals. Second was the tandem stereo cameras for information on the dynamics of aerosol plumes, followed by the aerosol limb imager for UTLS aerosols.

Balanced priorities

To converge on the final recommended architectures, the team sought observing systems that tried to achieve a balance between the three DS science focus areas. In general, this balance led to Ku radar and UV HSRL lidar capabilities being given highest priority as additions to the common building blocks for single-orbit solutions, followed by the tandem stereo cameras and aerosol and humidity limb imagers. For dual-orbit solutions, most of the augmentations to the common building blocks were focused on the inclined orbit, with Ku radar capability, tandem stereo cameras, and enhancement of the passive microwave radiometer being the top three priorities. The next priority was the addition of the UV HSRL channel to the lidar in polar orbit. The remaining priorities were time-differenced passive microwave radiometer measurements, a SW spectrometer, and then the aerosol and humidity limb imagers in the inclined orbit.

9.2 Final Recommended Architecture

Three architectures were considered for the final recommendation to NASA. The first two, designated P1 and P2, described in Appendix A, are polar-orbiting-only solutions that try to maximize the science capabilities in that orbit but at a cost of delaying launch until the 2031 time frame. The third architecture, chosen as the top recommendation for implementation, is a dual-orbit solution consisting of two stages: an earlier launch in the 2028 time frame with somewhat less capable instruments in an inclined orbit for characterizing diurnal variability and a later (2031) launch of a very capable set of instruments in polar orbit. While the early science phase in the inclined orbit does not meet the threshold science objectives of ACCP, it provides innovative measurements of diurnal variability and makes progress on ACCP and DS science objectives within the decade following the DS report. More details on the rationale for the selection are described in the Value Framework baseball cards in Appendix B. A description of the dual-orbit recommendation is below.

9.2.1 Instrument capabilities of the dual-orbit architecture

The inclined-orbit portion of the architecture starts with the respective common building block described previously (W, Ka band radar; microwave radiometer, backscatter lidar, and coarser resolution/ wider swath polarimeter), and implements the first two prioritized augmentations (Ku band, tandem stereo cameras) in the balanced-approach prioritization. Thus, it includes the following instruments [instrument characteristics taken from top instrument library (section 8.1) options]:

- **W- and Ku-band Doppler radar** for vertical profiling of clouds and precipitation. The radar uses DPCA Doppler capability at Ku band and single-antenna Doppler at W band in order to fit on a hosted payload bus. Both frequencies provide profiling capability to within several hundred meters of the surface. The W-band radar observes at nadir only, has a footprint of ~1 km, and a minimum detectable reflectivity above the surface clutter zone of –25 dBZ. The Ku-band radar has a narrow swath, footprint of ~5 km, and a minimum detectability of 10 dBZ at nadir.

- **Sub-mm passive microwave radiometer** for constraints on ice water path, ice properties, precipitation, and horizontal context. The radiometer is conically scanning with frequencies near 118 (4 channels), 183 (4 channels), 240, 310, 380 (4 channels), 660 and 880 GHz. The swath width is 750 km and fields of view range from 16x24 to 6x10 km (from lowest to highest frequencies).

- **Backscatter lidar** for profiling of aerosol and cloud properties using frequencies at 532 and 1064 nm.

- **Multi-angle, UV-VIS-SWIR Polarimeter** for aerosol and cloud properties. It has 10 channels and measures at 10 angles for most channels (60 at 670 nm), with a horizontal resolution of ~1 km and swath width of ~900 km.

- **Tandem stereo cameras** for measuring low cloud/aerosol plume properties and dynamics.

The polar component of the architecture, which is required to meet the ACCP threshold objectives, is composed of the common building blocks for the polar orbit:

- **W- and Ka-band Doppler radar** for vertical profiling of clouds and light-to-moderate precipitation and Doppler velocities. The radar uses DPCA Doppler capability at both W and Ku band. Both frequencies provide profiling capability to within several hundred meters of the surface. The W-band radar is nadir only, has a footprint of ~1 km and a minimum detectable reflectivity above the surface clutter zone of –25 dBZ. The Ka-band radar has a narrow swath, footprint of ~2.2 km, and a minimum detectability of 0 dBZ.

- **Sub-mm passive microwave radiometer** for constraints on ice water path, ice properties, and horizontal context. The instrument capabilities are identical to those in the inclined orbit.

- **HSRL lidar** for profiling of aerosol properties (type, microphysics, optical) and cloud properties. The lidar has frequencies at 532 and 1064 nm, with HSRL capability in the former channel.

- **Multi-angle, UV-VIS-SWIR Polarimeter** for aerosol and cloud properties. The polarimeter adds an additional channel at 940 nm and has twice the resolution, but about half the swath width as in the inclined orbit.

- **Spectrometers** for cloud and aerosol radiative fluxes. This capability is provided by two spectrometers that together span the spectral range from UV-VIS-NIR-SWIR-LWIR-FIR. Horizontal resolution is 200-400 m.

9.2.2 Key benefits

One of the key motivating factors for the selection of this architecture is that it provides (a) diurnally varying observations relevant to both aerosols and clouds, convection, and precipitation science and (b) early science within the decade of the Decadal Survey study with the launch of the inclined orbit component in the 2028 time frame. The architecture recognizes that deep convection, and its attendant heavy precipitation, is most frequent at low-to-mid latitudes and exhibits a strong diurnal cycle that is coupled to high-cloud evolution and atmospheric moistening. Therefore, the inclined-orbit component includes the Ku-band Doppler radar in the sensor package that maximizes capability for deep convection. Additional information on key variability of aerosol emissions, particularly biomass burning, will extend the lidar data record begun by the CATS mission, with a key advance being the coupling of the lidar with a polarimeter for improved aerosol retrievals.

Profiling of clouds and precipitation

ACCP builds on previous missions in several key ways. While less sensitive than CloudSat CPR, the ACCP radar makes significant advancements in profiling of clouds and precipitation by providing multi-frequency (W-Ka in polar, W-Ku in inclined) radar measurements to sample drizzle to moderate precipitation in the polar orbit and drizzle to heavy rainfall in the inclined orbit. The radars will also provide measurements down to ~300 m of the surface compared to ~700 m from CloudSat and 1-2 km from GPM. This capability will allow for measurement of precipitation falling below cloud base in low clouds and to better detect phase changes from snow to rain close to the surface. The lidars will provide additional cloud profiling capability for non-precipitating clouds that cannot be detected by the W-band radar and will allow for combined lidar/radar retrievals for mixed phase detection, ice and liquid water content, and detection of the full spectrum of clouds.

Measurement of in-cloud vertical air motions

The Doppler capabilities for ACCP will provide significant improvements relative to EarthCare in precipitating regions. For the polar-orbiting satellite, the W- and Ka-band radars will use the dual-antenna (DPCA) approach that will reduce noise and errors associated with non-uniform filling of the radar beam. While the W-band radar will be unable to detect weak cloud signals due to its less-capable sensitivity than CloudSat and EarthCare, its Ka-band radar will provide improved measurement in moderate precipitation and improved downward penetration within areas of convection. For the inclined orbit, the W-band radar performance will use a single antenna and be comparable to EarthCare in terms of noise and non-uniform beam filling effects, but the Ku-band radar will provide DPCA performance and will penetrate most convection, allowing the first-ever measurements of vertical motions in deep convection around lower and midlatitude portions of the globe where deep convection is most frequent.

Doppler capability will also be valuable for particle phase and possibly microphysics information. For precipitation sized particles, ice particles generally have much smaller fall speeds than raindrops so that phase transitions associated with snow melting into raindrops show up as a marked increase in fall speeds and are readily detectable in the Doppler signal. When combined with the multi-frequency radar reflectivity data, the Doppler signal may also provide information on the mean particle sizes of precipitation particles.

Profiling of aerosol optical and microphysical properties

The inclined orbit backscatter lidar will have improved SNR performance in both day and night compared to CALIPSO and CATS and will provide information on diurnally varying processes related to aerosol emission and transport. Polarimeter measurements during the day will provide additional constraints on retrieval of aerosol properties.

In the polar orbit, the inclusion of an HSRL channel at 532 nm will enable high-quality information for air-quality, aerosol intensive properties, aerosol radiative effects and aerosol-cloud interactions. High SNR and direct measurement of particulate backscatter provide unprecedented day/night profiling of aerosols compared to previous lidars.

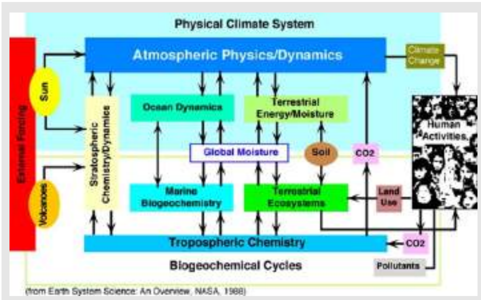
Pollutant characterization and aerosol removal/redistribution in light to heavy precipitation is reasonably well served by the lidar, polarimeter and radar combinations in both orbits.

Coupled cloud-aerosol-radiation measurements

The polar component of the architecture provides key measurements for low- and high-cloud radiative effects and direct and indirect aerosol radiative effects. It will provide the first ever collocated (in time and space) measurements of cloud dynamics, cloud and precipitation microphysical properties, aerosol properties, and cloud-scale radiation measurements.

Tandem stereo cameras

Unique measurements will be obtained from a pair of stereo cameras spaced about 45 seconds apart that will provide accurate measurements of cloud or aerosol plume height and its change over the short time interval. This time-differenced approach will enable calculation of horizontal and vertical motions at cloud or plume top, associated horizontal divergence, and estimates of cloud entrainment rates, which are of particular interest for low stratocumulus cloud decks.



BOX ES: ACCP—An Earth Systems Science and Applications Measurement Program

The so-called 'Bretherton report' (NRC 1986) cemented the idea of Earth System science into our thinking. That report identified two primary conclusions that have essentially framed the Earth-System science concept since then:

(i) Changes on planetary scales are the result of interactions and feedbacks among Earth sub-systems,

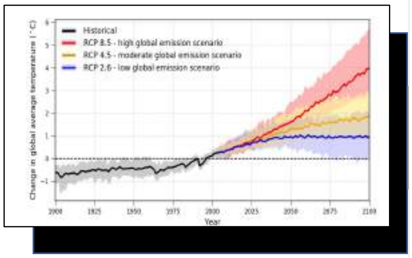
(ii) Changes on any temporal scale involve interactions among Earth-system processes that occur across diverse time scales.

The challenge underlying these conclusions is the need to observe, quantify and understand the consequences of interactions between processes on different time and space scales. The implications for observing Earth as a system are profound and our ability to understand and predict the evolution of the Earth system requires an integrated systems approach to observing Earth.

This Earth-systems viewpoint permeated the DS report and its recommendations. The report notes:

"Earth is a dynamic planet on which the interconnected atmosphere, ocean, land, and ice interact across a range of spatial and temporal scales…Today's leading science often occurs at the system level, with the aim of understanding the linkages between these elements, the processes that connect them, and how variability occurs among them…Since Earth is our home, our survival and quality of life depend on how well we understand its behavior. A commitment to monitoring, understanding, and predicting complex and dynamical Earth systems is a scientific and societal imperative."

How to observe the more interactive aspects of such an Earth system to develop a systems-level understanding has been recognized as a major challenge for some time. Making joint measurements of multiple parameters on one platform, for example, was the motivation of the Earth Observing Systems (EOS) platforms (Asrar and Dozier, 1994) originally referred to as EOS-A and B and now as Terra and Aqua. NASA's A-Train constellation of satellites has since offered a blue-print of sorts for how a more integrated observing approach might be constructed in the form of a multi-sensor constellation. ACCP embodies an Earth systems approach observing from specific connected components from different vantage points across diverse space and time scales (e.g., Figure 1.1).



BOX CDR: ACCP as Part of a New Climate Data Record

A major challenge across the Earth sciences is to identify secular changes in key Earth system variables above natural variability and then assign these changes to a climate forcing. This is especially true of the properties of cloud and precipitation defined by processes operating over vast time and space scales. These secular changes will determine the magnitude of climate warming; observations of them are needed because confidence of such changes in climate models is low. The GEWEX clouds assessment study (Stubenrauch et al. 2012, 2013; Fig. CDR-1), for example, concluded that over the existing 25 years of global satellite cloud records assessed, cloud properties deduced from multiple sources of data have remained constant within the range of the interannual variability of these properties. These clouds properties, however, come with ambiguity that act to mask the changes that are occurring.

One of the obvious advantages of active measurements of clouds is the unambiguous measure of their vertical distribution and by implication a more direct way to determine any changes to these vertical distributions. Two studies of note that explore this within the context of forced cloud profile changes are those of Chepfer et al (2014) and Takahashi et al (2018) respectively framed around lidar and W-band radar profile information.

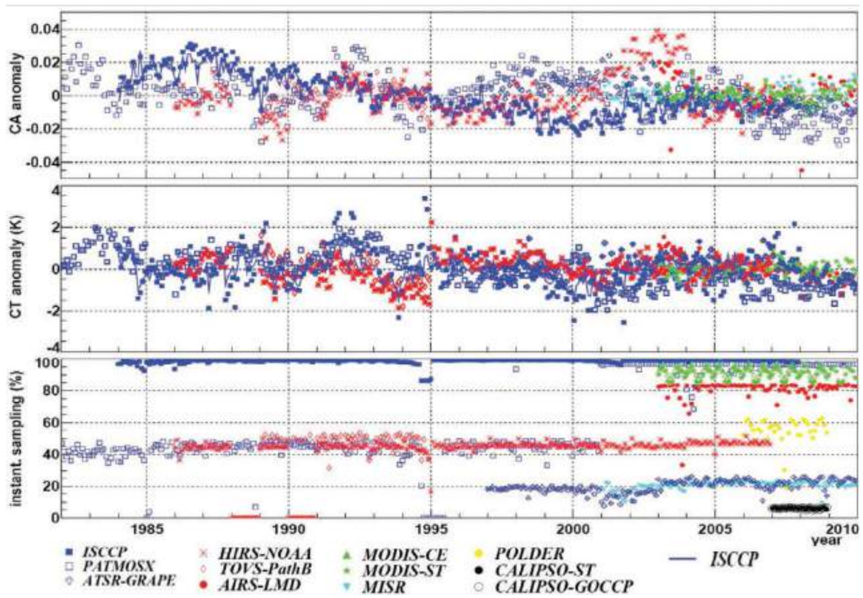


Figure CDR-1: The 25-year cloud amount (upper), cloud-top temperature (middle) global anomaly derived from multiple, popular cloud data records. The lower panel shows the mean instantaneous sampling of the globe, expressed as a fraction, for the various datasets. From Stubenrauch et al. 2013.

Chepfer et al. argue that changes to cloud cover and cloud vertical distributions, as observed by spaceborne lidars, offer a more robust signature of climate change than passive sensors based on analysis of climate model simulations from the CMIP present day and +4 K experiments. The analysis showed that cloud radiative effects and total cloud cover (analogous to the variables of Figure CDR-1) do not represent robust signatures of climate change given that predicted changes of these variables lie within the range of variability in the current observational record. By contrast,

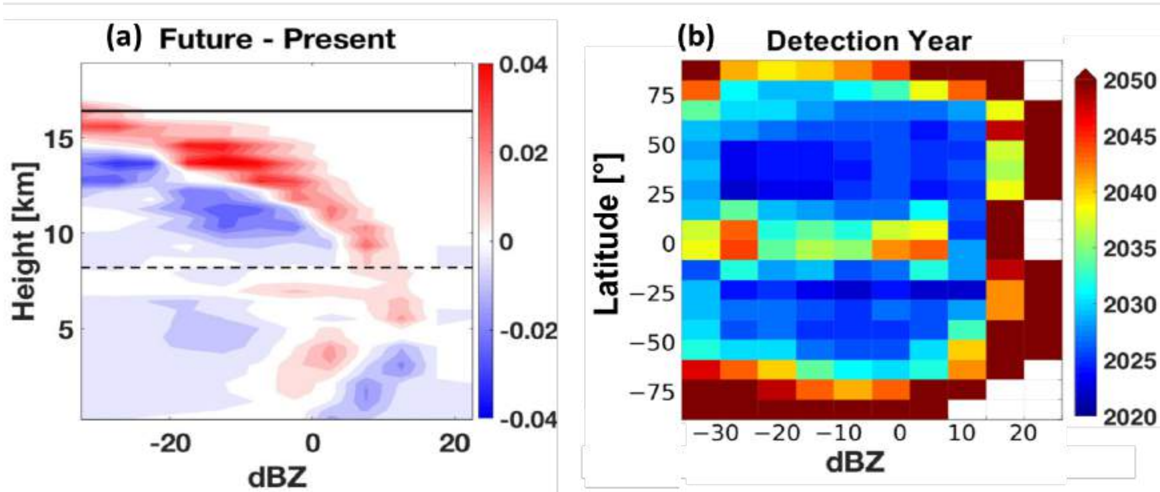


Figure CDR-2 (a): The difference in lidar inferred cloud profile changes cloud between present day and a +4K warmed surface deduced from two different models (orange and blue). The shaded profile represents the natural variability of the profile (Chepfer et al. 2014). (b) Differences between Future and Present CFADs for the latitudes between 0-10°N from CESM1 simulations. There is a clear upward shift in the clouds at reflectivities<0 *dBZ*. (c): The year when statistically significant and climatologically stable trends would be detected as a function of latitude and radar sensitivity. There is greater statistical significance in lower reflectivity cloud -mode observations (Z<0 *dBZ*) and little significance to precipitation related reflectivities (Z>10 *dBZ*) (Takahashi et al., 2018).

the predicted forced changes in cloud vertical distribution result in much larger and more readily detected change (Figure CDR-2a) which are expected to first appear at a statistically significant level in the upper troposphere, at all latitudes. Chepfer conclude that an approximate 25-year record of lidar cloud top data is sufficient to detect significant cloud changes over and above internal variability.

Takahashi et al (2018) found significant upward shifts in clouds (Figure CDR-2b) expressed by W-band radar reflectivity profile changes and concluded that statistically significant trends would be detected as early as the mid 2020's in the worst-case-warming scenario (Figure CDR-2c) with an extended-in-time W-band radar record. This detection occurs earlier than that of lidar profile changes and appears first in the mid-latitudes because the natural variability in the tropics largely masks early detection there.

BOX CI: Aerosol and Convection Intensification

Aerosol influences on precipitation has a tortured history, being rooted in the weather modification discourse with the ambiguities surrounding that entire enterprise (e.g., Stephens et al., 2020). Much speculation also exists on the influence of aerosol on convection itself with suggestions that aerosols, through a microphysical and latent heating pathway, affect storm updrafts and convective precipitation (Box CI-1). Modeling studies of aerosol impacts on deep convection have shown that precipitation and convective updrafts may increase, decrease or change little with increased aerosol loading (Tao et al 2012; Boucher et al 2013). Such responses to aerosols may be modulated by the environment (Khain et al 2008; Storer et al. 2010; Grabowski 2018), aerosol type (van den Heever et al 2006; Fan et al 2018), aerosol altitude (Fridlind et al 2004), cloud phase (Rosenfeld et al 2008; Koren et al 2014), and cloud lifecycle (van den Heever et al 2006). However, when the responses to aerosols are considered over regional domains instead of a cloud-by-cloud basis, precipitation shows a limited integrated response (Grabowski and Morrison 2011; van den Heever et al 2011; Seifert et al 2012) due to inter- and intra-cloud competing processes, suggesting that such systems are buffered (Stevens and Feingold 2009). Clear evidence for the influence of aerosol on convection, however, is generally lacking with the usual difficulty in establishing cause and effect in real world data. Today, our understanding of the aerosol influence on convection remains rudimentary. ACCP is expected to provide important information about the processes that are central to making advances on this topic.

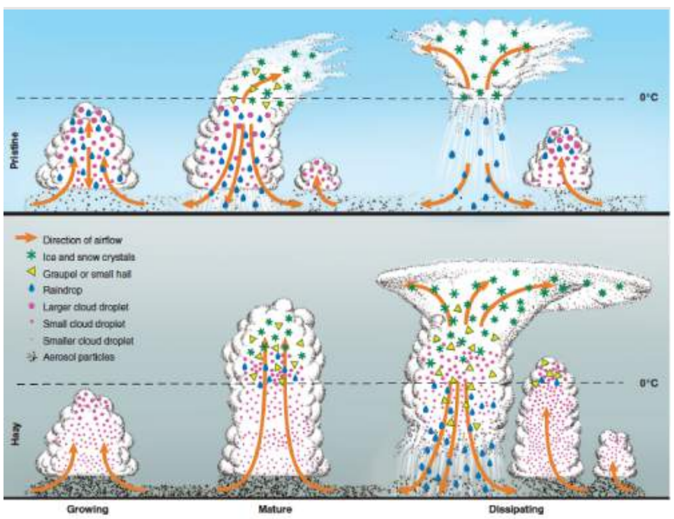


Figure CI-1. Hypothesized evolution of deep convective clouds developing in the pristine (top) and polluted (bottom) atmosphere. Cloud droplets coalesce into raindrops that rain out from the pristine clouds. The smaller drops in the polluted air do not precipitate before reaching the supercooled levels, where they freeze onto ice precipitation that falls and melts at lower levels. The additional release of latent heat of freezing aloft and reabsorbed heat at lower levels by the melting ice implies greater upward heat transport and more intense convection (Rosenfeld et al. 2008).

Unlike weather modification for which causality, and the lack of a large data base to detect it, has been a long-standing challenge (NRC, 2003), a large body of observational evidence of aerosol influences on clouds exist where cause and effects can be more clearly established. Ship tracks are observed localized changes in clouds due to large injections of aerosol from emissions from ship stacks that create localized perturbations to boundary layer clouds. Cloud differences between regions immediately influenced by these emissions and adjacent cloud regions free of the immediate influence suggest an observational framework for understanding aerosol cause and effect on clouds. The influence of volcanic emissions on clouds (Schmidt et al., 2012; Ebmeier et al., 2014; Gettelman et al., 2015 and Malavelle et al., 2017) offer another potential natural test case and thus a possible way for constraining models on a much larger scale than can be achieved with ship track data. Periodic Saharan dust intrusions over the eastern Atlantic Ocean also provide another natural laboratory for evaluating dust impacts on convection intensity (Koren et al. 2005; Storer et al. 2014), with the sibling papers of Herbener et al (2016) and Sauter et al (2019) demonstrating the use of satellite measurements in determining dust transport by hurricanes and evaluating these in models.

The study of Thornton et al (2017) is an example of ship track influences on convective clouds identified by lightning differences from strong storms in and out of ship tracks. Strong convection lifts cloud drops up to high altitudes where freezing occurs and collisions between drops, graupel, and ice crystals electrify the storm. Lightning is thus an indicator of storm intensity and generally sensitive to the profile of where cloud drop formation occurs, where interactions and freezing exist and the degree to which water is lofted into ice regimes. Thornton et al find that lightning is nearly twice as frequent in the shipping lanes in the Indian Ocean and the South China Sea (Figure CI-2) than in surrounding areas. The lightning enhancement clearly maximizes along the paths of ships. It is reasonably hypothesized that these lightning enhancements stem from aerosol emitted by ships traveling along these routes affecting the microphysical processes and thus formation of lightening. As in the case of cloud ship tracks, these particles act as the nuclei on which cloud drops form, changing the vertical development and structure of storms as Rosenfeld et al hypothesized, allowing more cloud water to be transported to high altitudes, where electrification of the storm occurs enhancing lightning thereby providing a clear example of aerosol influences on deep convection. The studies of Christensen et al (refs) have shown how narrow swath A-train lidar and radar data, accumulated over time, provides thousands of ship track intersection that were used to provide basic insights on processes that determine aerosol cloud effects in shallow clouds. ACCP now offers a similar opportunity to study these lightening tracks and thus address basic questions about aerosol influences on deep convection, such as is storm intensity, measured more directly by vertical velocity, enhanced in these tracks as implied, and is the profile of hydrometeor change commensurate with the hypothesis?

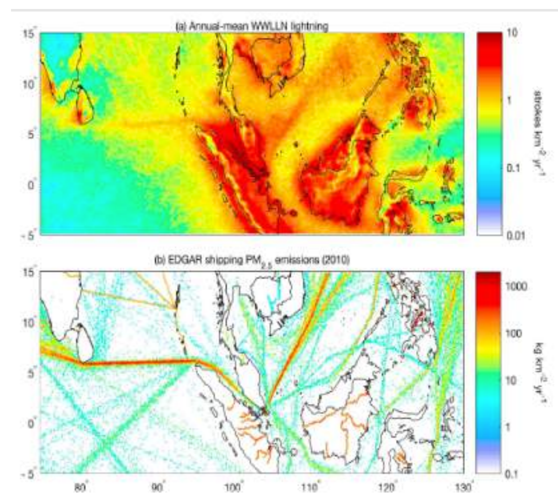


Figure CI-2. (a) Observed annual-mean World Wide Lightning Location Network (WWLLN) lightning density for 2005–2016 in the eastern Indian Ocean and the South China Sea. (b) PM2.5 shipping emissions estimates from EDGAR database for 2010, both at 0.1° resolution (Thornton et al., 2017).

BOX R: Global Risks, Severe Weather and ACCP

The World Economic Forum report on global risks identified extreme weather as the top-most likely global risk confronting humanity and further declared this risk to be among the top four most impactful to world society (Figure R-1). This particular risk is further highlighted in the NOAA annual inventory of the cost to the US of extreme weather events also shown in Figure R-1(right). Between 2015-2019, severe weather accounted for more than 3500 deaths and over $500B in damages. Furthermore, the number of events and the total losses from them have systematically increased in the US over time.

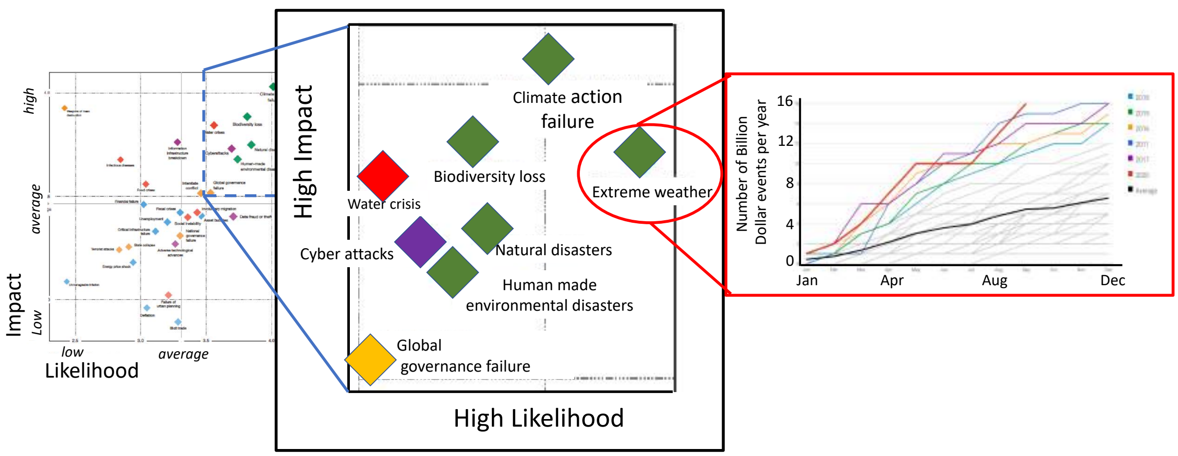


Figure R-1. The global risks landscape of 2020 (left and center) according to the World Economic Forum. Of the ten classes of risks identified, the highest risks are all environmental with weather extremes being the most likely and among the most severe of all risks for the global society. NOAA maintains an inventory of the severe weather impacts that arise from flooding from intense rainfall, hail damage, wind damage from convective and tornadic storms, and hurricanes. The number and cost of these events have been increasing over time. Left and middle panels adapted from Global Risks Report (World Economic Forum, 2020). Right image from https://www.ncdc.noaa.gov/billions/overview.

Understanding how weather extremes are changing in a warming world, advancing our ability to predict their occurrence and likely impacts are all aspects of a grand challenge confronting Earth sciences. This challenge was noted in the 2017 Decadal Survey report that considered the topic of extremes to be an important context for the priorities called out in that report. The report also identified the following requirements for advancing the predicting high-impact extreme events:

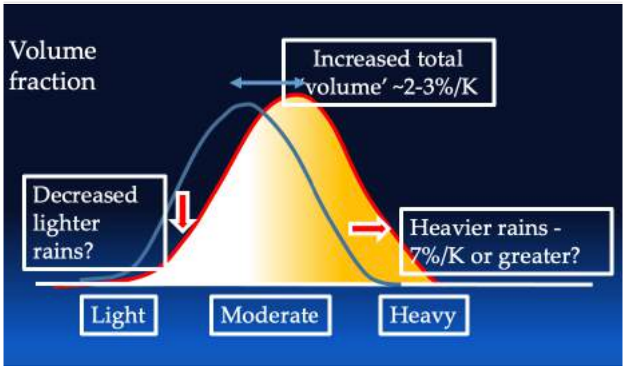


Figure R-2. A schematic of the different ways the precipitation distribution is thought to change with warming. The distribution shifts to more frequent heavier precipitation (source TBD).

• *Monitor global and regional trends of extreme events and impacts*. High-impact extreme weather events are by nature infrequent and represent the tail of the distribution of relevant variables used to define them (e.g., Figure R-2). Capturing these events and documenting how they change over time and on a wide range of temporal and spatial scales requires observing and analysis systems that are both sustained over time and comprehensively sample over space. Sustained monitoring provided by networks of operational satellite meteorological systems, for example, are essential building blocks for monitoring extreme weather. ACCP will contribute indirectly to this requirement by providing a more direct measure of extremes which will serve as a way of calibrating the less direct measures of the variables derived these operational systems that are used s measures of extremes.

• *Observe state variables that best represent multiscale and multicomponent interactions leading to extreme events*. The strength of vertical motions in storms fundamentally define most of the properties typically used to characterize severe weather. Observing this

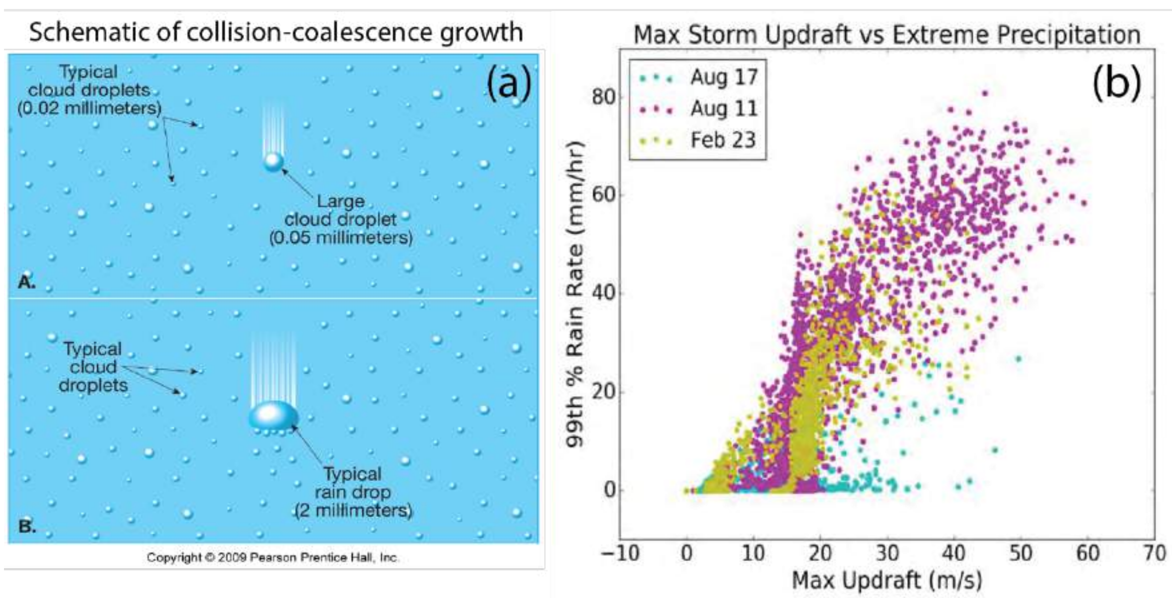


Figure R-3. The maximum column updraft speed is a fundamental measure of convective intensity correlating to greater rain droplet growth by collision and coalescence (a, source TBD) and development of more extreme precipitation produced by storms (b, from Stephens et al. 2020). The relationships shown in (b) are derived from cloud resolving model simulations of convective storms. This maximum speed also connects to the environmental conditions and ACCP will help address why not all storms of the same environmental conditions produce extreme weather responses.

dynamical state variable is unique to ACCP. The rudimentary influence of the vertical motion that will be observed on the properties of extreme weather can be simply understood in terms of the processes that produce rain, hail and lightning. Strong updrafts imply much deeper clouds, loft cloud water drops high into upper region where ice particles grow by riming, forming hail. The stronger the updraft, the greater the potential for damaging hail, which is typically associated with very deep, vigorous storms. Similarly, the larger the updraft, the greater is the path by which rain drops form by coalescence (Figure R-3a) and the greater the likelihood for large rain drops and extreme precipitation (Figure R-3b). Furthermore, the stronger the updraft, the deeper is the layer of water and ice mixtures that forms and the greater the likelihood of storm electrification. These different properties of storms are determined by vertical motion and its vertical structure which is information that ACCP will provide. This will transform our understanding of processes responsible for extreme weather.

• *Quantify uncertainty and improve prediction and long-term projection of extreme events in a changing climate*. Modelling and prediction of extreme weather can be expected to make significant strides in the coming decade as a result of the modelling initiatives described in Box DE. Increased resolution of models will directly impact their ability to represent vertical motion properly and thus the representation of processes that determine the distribution of these properties (Figure DE). ACCP will play a basic role in these model and prediction developments by providing tests of processes and relations between storm intensity, the environment in which they form, and the key variables used to measure extreme weather.

BOX GEO: ACCP and the Geostationary Program of Record

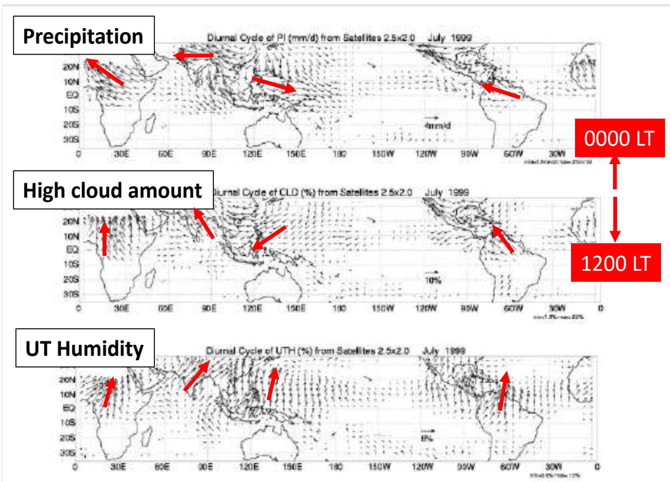


Figure BG-1: The phase and amplitude of the diurnal cycle of variables (precipitation, an index of convection; high clouds and upper tropospheric humidity), each connected to the other lagged in time and observed using spectral radiances from the geo-PoR. The phased connections between these variables are central to aspects of high cloud feedbacks and the influence of convection on these feedbacks. Matching this PoR information to ACCP measurements offers a unique process perspective on these connections and feedbacks (Tian et al. 2004).

The capabilities of geostationary satellites for providing spectrally diverse observations of Earth have expanded significantly over the past decade. Today we now have quasi-global coverage from the fleet of multi-agency meteorological geostationary satellites providing a common set of 11 spectral channels of both shortwave and infrared (IR) radiances offering unprecedented space, time and spectral coverage of Earth. The creation of a homogenized geo-ring of such data is underway though an international coordination across satellite meteorological agencies driven by the recognition of the enormous potential of such data for science and applications. There are many important ACCP uses of these GEO-ring radiance data ranging from providing advanced cloud and aerosol detection and property estimation, to the expression of such information as a function of time providing further insights on convective storm lifecycle processes and environmental responses to these storms (Figure BG-1).

Exploiting the geostationary program of record (geo-PoR) is an essential element of the ACCP Earth system approach. The ACCP application of the geo-PoR will be part of a much larger and developing international engagement that is highlighted with the organization diagram presented as Figure BG-2. The effort begins with oversight by the CGMS, an international body who coordinate activities across the constellation of geostationary satellites. An important aspect of the CGMS oversight is the maintenance of common methodologies for cross calibration of these geostationary radiance data by the Global Space-Based InterCalibration System (GSICS) working group of the CGMS. This group at present only provides calibration methodologies for a restricted number of channels and even then with some limitations (e.g. Fiolleau et al. 2020). The effort is to be expanded to include more channels. With GSICS guidance, a cross calibrated quasi-global, homogenous and multispectral radiance data product (the level 1g product in the figure) will be

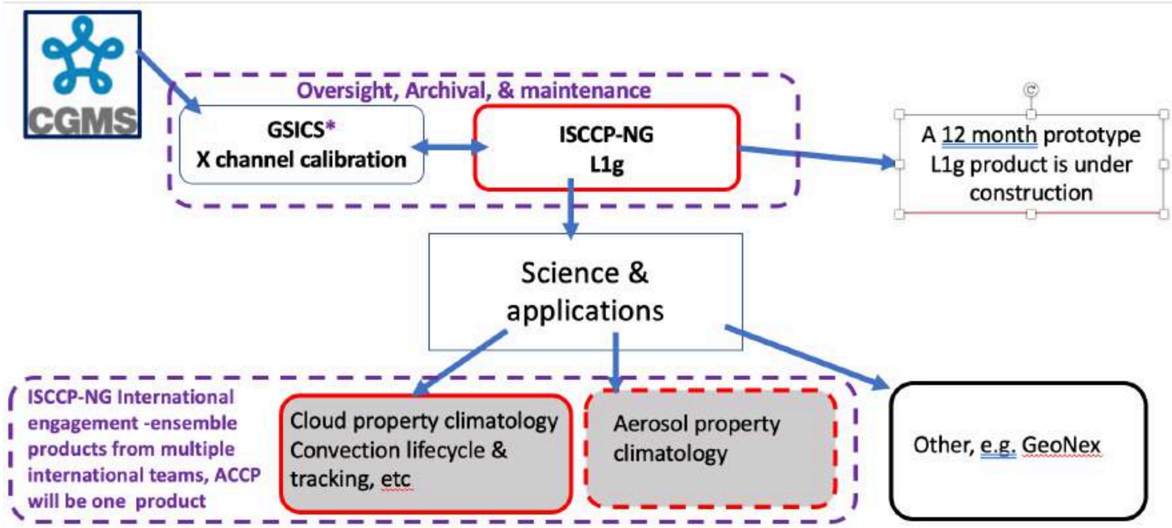


Figure BG-2: A schematic of the way the ACCP geo-PoR will develop as part of a larger international effort in partnership with CGMS and WCRP GEWEX oversight. The activities called out by red boarders and shaded are efforts expected to be developed under ACCP. The ISCCP focus is initially on cloud climatologies with ACCP contributing in important and unique ways such as providing calibration using ACCP profile data. It is expected that ACCP will lead the aerosol product development for the community.

created. This data product will then fuel many applications and its stewardship will fall in part to the international WCRP GEWEX program working with the CGMS. GEWEX is championing the creation and use of this level 1g for producing a new generation cloud climatology (hereafter ISCCP-NG) which is to be a follow-on from the highly successful ISCCP. GEWEX will oversee an ensemble of multiple cloud products derived from the level 1g radiances by different groups worldwide. One of these products is expected to be that developed specifically for ACCP that would also be augmented with aerosol properties derived from the same level 1g radiances. It is expected that ACCP would provide leadership in developing the products from this level1g.

Box DE: Expected Modelling Evolution

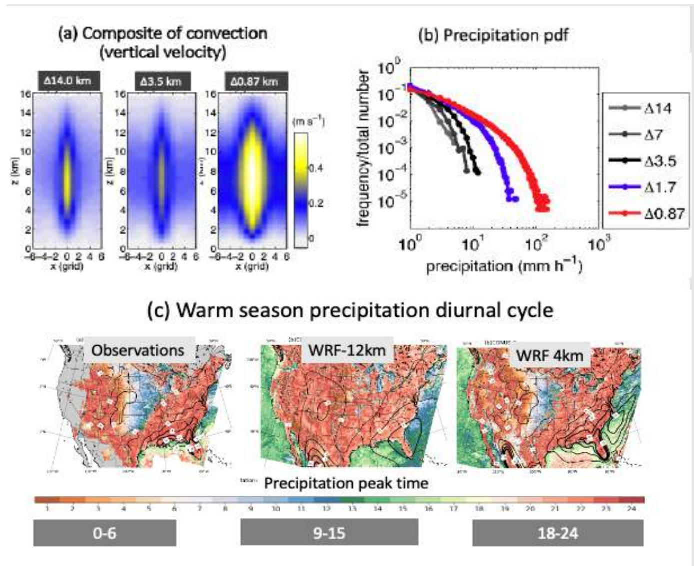


Figure DE Three dramatic examples of how eddy resolving global and regional simulations impact simulations of convection. (a) The global composite of vertical motion, showing how increases resolution enhances the intensity of updrafts, (b) The pdf of global precipitation illustrating how the occurrences of more intense precipitation increase with model resolution (Δ14=14km resolution, etc.) and c) the diurnal cycle of warm season precipitation, dominated by convective storms that form over the Rockies and propagate westward. From Stephens et al. (2021, BAMS, in preparation).

Today, typical models of the Earth system – including its atmosphere, ocean, cryosphere, biosphere and other processes, are limited by the present-day computation power to spatial resolutions of 50 to 100 kms; even leading weather forecast models, like that of ECMWF, operate at resolutions of ~10 kms. However, even these weather models are moving their resolution to the 1km scale (k-scale) with demonstrations of 1-4km global simulations now being performed by a number of modelling centers. These modeling efforts have been termed 'digital twins' of the Earth (so called because they appear more realistic in pseudo-satellite efforts) and are being developed in the coming decade by different centers, and in coordinated projects such as DYAMOND (Stevens et al., 2019). These efforts will simulate the atmosphere, ocean, ice, and land with unrivaled precision, providing forecasts of floods, droughts, and fires from days to years in advance. The WCRP Digital Twin effort also strives to capture human behavior whose imprint becomes increasing important as focus is at finer and finer resolutions.

Moving toward k-scale earth system modelling represent a major step forward in capability (Slingo et al., 2021). For example, processes that govern extreme weather on fine scales, especially motions within convective storms, are not well represented in global models and currently not well observed. Global storm and ocean-eddy resolving [of order 1 km] models make it possible to directly simulate deep convection (Fig. DE) more realistically, ocean mesoscale eddies, and important land–atmosphere interactions. Selected results from prototypes from two such models are highlighted in Fig. DE emphasizing important improvements in the representation of storms, severe weather and their diurnal cycle. It is anticipated that such improvements will reduce or even eliminate many systematic biases that plague the present generations of models especially related to the vertical transport of heat critical to the formation of clouds and storms, topics that are keenly central to ACCP objectives.

Tests of the realism of future high-resolution models will require new observations of aerosol, storm and cloud dynamics, and ACCP will provide a necessary global constraint on these processes. The convergence of ACCP and high-resolution modeling initiatives in this coming decade offers enormous potential for new applications, offering decision makers the ability to assess the impacts of weather events and climate change on society, and the means to better gauge the effects of different climate policies.

Box O: ACCP Below The Ocean Surface

Passive radiometric imagers have provided more than a 23-year continuous record of global plankton properties that has revolutionized the understanding of the ocean ecosystem. Despite this, passive ocean color measurements have limitations. For instance, the passive ocean color retrievals provide data heavily weighted close to the ocean surface, provide no information on vertical structure of biomass below the surface, are valid only under clear sky conditions and only during the daytime when sun elevation angles are sufficiently high thus missing low elevation polar regions. Ocean profiling lidar overcomes these deficiencies, providing a natural complement to these passive measurements. The potential of lidar for studying aquatic ecosystems was noted in the 2017 DS with the recommendation that the lidar system considered by ACCP should seek to provide, if possible, this added capability.

"Depending on implementation specifics, a lidar may also contribute to aquatic ecosystem structure, ocean mixed layer depth, ice-sheet topography, land topography, and PBL height. In particular, many of the scientific and technical opportunities and challenges for a joint aerosol-ocean measurement system have been mapped out in some detail as part of the planning for the ESAS 2007 Aerosol/Cloud/Ecosystems (ACE) mission ....The Aerosol Targeted Observable instrument and mission design, therefore, should seek to address these interdisciplinary objectives while recognizing that the primary mission focus is meeting the aerosol science objectives as described and remaining within the cost cap. Opportunities should be assessed to determine the extent to which these additional science goals can be achieved while also meeting the aerosol science objectives and maintaining overall costs at or below the recommended cost cap."

The CALIOP lidar on CALIPSO offered an important illustration of the value of spaceborne lidar for studying aquatic ecosystems. Although the vertical resolution of that lidar was too coarse to enable true ocean profiling, CALIOP data have been used in several studies to advance ocean science. CALIOP notably has filled in high-latitude fall-winter-spring seasonal gaps in the existing ocean color record enabling an improved understanding of the plankton seasonal cycle at higher latitudes. The CALIOP lidar was able to acquire data in frequently cloudy regions due to the ability of the lidar to penetrate small holes in broken cloud systems without the confounding influence of 3-D side scatter from nearby clouds. Day-night differences in the CALIOP signal also have been used to quantify the diurnal vertical migration of zooplankton and other marine animals that graze on phytoplankton.

The ACCP HSRL is a major advance over CALIOP for both and atmospheric remote sensing. Faster electronics allows much finer vertical resolution measurements below the ocean surface (~1-2 m vs. ~25 m for CALIOP) thereby providing the means to acquire actual subsurface profiles. Unlike CALIOP and past ocean color retrievals, the ACCP HSRL can independently retrieve depth-resolved profiles of ocean attenuation and particulate backscatter coefficients. These profiles will provide the first-ever global measurements of the vertical distribution of biomass and enable improved estimates of net primary production and carbon stocks. The ACCP HSRL will also provide the vertical profile of depolarization, which, together with the profiles of attenuation and particulate backscatter, will provide information on phytoplankton community composition. The high-vertical-resolution capability of the ACCP HSRL provides advanced ocean profiling, enables cloud measurements, and enhances specific calibration functions. Therefore, this cross-cutting ocean capability comes at no extra cost or risk, and the impact of the ocean samples on the downlink data volume is insignificant compared to the atmospheric signals.

Adding backscatter and HSRL channels in the UV (355 nm) would also provide significant benefits, even though these channels would have coarser vertical resolution (~10 m) than in the visible. Differences in attenuation between the 355 and 532 nm wavelengths will enable separating color dissolved organic matter (CDOM) absorption from chlorophyll absorption. Differences in particle backscatter at the two wavelengths will provide additional insights on phytoplankton community composition and, possibly, the slope of the size distribution.

Appendix A—Alternative Architectures

A.1 Polar-orbit only — Architecture P1

Instrument capabilities

- **W- (nadir only) and Ka-band (15 km swath) Doppler radars** for vertical profiling of clouds and precipitation and Doppler velocities
- **JAXA Ku-band Doppler radar** (255 km swath) for vertical motions and precipitation in heavy precipitation
- **Sub-mm passive microwave radiometer** (118, 183, 240, 310, 380, 660, 880 GHz) for constraints on ice water path, ice properties, precipitation, and horizontal context
- **Three-channel (355, 532 nm HSRL, and 1064 nm backscatter) lidar** for profiling of aerosol properties (type, microphysics, optical) and cloud properties
- **Multi-angle, UV-VIS-SWIR Polarimeter** (0.5 km resolution, 550 km swath) for aerosol and cloud properties
- **UV/VIS/NIR/SWIR/LWIR/FIR Spectrometers** (200-400 km swath) for cloud and aerosol radiative fluxes
- **Tandem stereo cameras** (VIS) for measuring low cloud/aerosol plume properties and dynamics
- **Aerosol and humidity limb imagers** for upper-tropospheric/lower-stratospheric humidity and aerosols

Key benefits

- **Profiling of clouds and precipitation**
  - While less sensitive than CloudSat, makes significant advancement with improved precipitation profiling for low clouds and snowfall near the surface
  - Combined with JAXA radar, provides measurements for clouds to light-to-heavy precipitation, including GPM-like swath for precipitation measurement, 3D structure, and improved capabilities for applications.
  - Combined radar frequencies (primarily Ka/Ku) provide for estimation of precipitation particle characteristics.
  - Combined lidar/radar retrievals for mixed phase detection, ice and liquid water content, detection of full spectrum of clouds
- **Measurement of in-cloud vertical air motions**
  - Improved Doppler capability for convection than the EarthCare radar
  - Doppler capability valuable for particle phase and possibly microphysics information
  - Provides Doppler information for all cloud types, including low clouds, polar clouds, and heavy precipitation.
- Combined radar frequencies provide for estimation of precipitation particle characteristics, including size, density
- **Cameras** provide novel information on low cloud and aerosol plume dynamics
- **Profiling of aerosol optical and microphysical properties**
  - Most complete information for air-quality, aerosol radiative effects and aerosol-cloud interactions
  - Provides the best capability for determination of aerosol type and intensive properties

    - High signal-to-noise ratio (SNR) and direct measurement of particulate backscatter provide unprecedented day/night profiling of aerosols compared to previous lidars
- **Coincident shortwave and longwave radiation measurements**
    - Essential for addressing cloud and aerosol radiative forcing
    - Links cloud and aerosol vertical structures to radiative effects at the instantaneous footprint level rather than highly space and time averaged
- **Combined active-passive measurements**
    - Provides improved constraints on cloud, precipitation, and aerosol profile quantities
    - Provides swath for horizontal context for nadir measurements and improved applications

Value to the DS science questions

- **Climate Feedback (C-2):** Provides key measurements for low and high cloud feedback, direct and indirect aerosol radiative effects, and cold cloud process studies. Radar profiling to near surface and cameras offer significant advances for low clouds and snowfall. Aerosol and moisture limb instruments provide information for the important UTLS region.
- **Convection (W-4):** Provides capabilities for measuring vertical motions for shallow to deep convection, including swath for 3D structure and precipitation mapping, although radiometer footprints are large for convective studies. No information on how strongly varying processes change over the day.
- **Aerosol Processes (W-5):** Pollutant characterization and aerosol removal/redistribution in light to heavy precipitation is well served by the lidar, polarimeter and radar combination. Cameras add information on plume top motions, while aerosol limb imager provides UTLS aerosols related to vertical transport by convection, volcanoes, and pyrocumulus. Information on emissions would benefit from additional observations in inclined orbit.

A.2 Polar-orbit only — Architecture P2

Instrument capabilities

Similar to P1 but with the following differences:

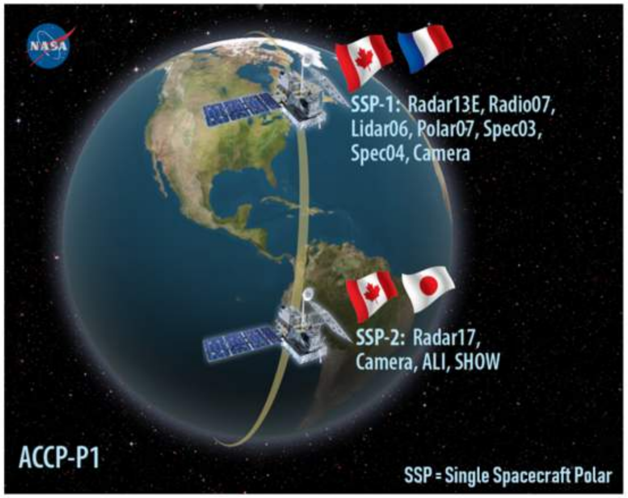
- JAXA Ku Doppler radar with precipitation swath replaced by domestic **nadir-only** Ku-band Doppler channel added to Ka/W-band radar
- No JAXA partnership and no JAXA-provided launch

Key benefits

Pros and cons relative to P1

- Pro: Spatially and temporally matched W, Ka, and Ku footprints
- Pro: Substantially reduced cost
- Con: No Ku-band swath for 3D precipitation structure, including convective core size, precipitation discrimination, and precipitation mapping
- Con: Lower applications value due to lack of swath

Appendix B—ACCP Baseball Cards



Instrumentation Highlights

Radar13E
W-Band Doppler, Nadir; Ka-Band Doppler, 15km Swath

Radar17
Ku-Band Doppler, 255km Swath

Radio07
118, 183, 240, 310, 380, 660, 880 GHz, 750km Swath

Lidar06
355nm & 532nm HSRL, 1064nm Backscatter

Polar07
Multi-angle, UV-SWIR, 550km Swath, 0.5km FOV

Spec03
LWIR, FIR, 400km Swath

Spec04
UV, VIS, NIR, SWIR, 200km Swath

Camera
Tandem Stereo Camera Visible Imaging

ALI
Aerosol Limb Sounder

SHOW
Water Vapor Limb Sounder

Polar = Polarimeter Radio = Radiometer Spec = Spectrometer

Science Narrative

Convective Storm Processes

Pros: Transformative capabilities for measuring vertical motions in shallow to deep convection. Measurements span light to heavy precipitation with 3 coincident frequencies, GPM-like swath for 3D structure and precipitation feature context. **Cons:** Radiometer footprints are large for convective studies. Lack of inclined orbit is detrimental to characterization of sub-daily convective processes.

Air Pollution and Distribution

Pros: Lidar, polarimeter, radar combination provides unprecedented particulate characterization and information on aerosol removal/redistribution in light to heavy precipitation. Tandem stereo cameras add information on plume top evolution, while ALI provides information on extreme volcanic/smoke events and their relation to vertical transport by convection. Lidar UV channel enables better characterization of aerosol type, size, absorption, concentration. **Cons:** Lack of inclined orbit is detrimental to characterization of sub-daily aerosol processes.

Climate Sensitivity and Feedback

Provides broad diversity of measurements for low and high cloud feedback, direct and indirect aerosol radiative effects, and cold cloud processes. Radar profiling to near surface offer significant advances for low clouds and snowfall; tandem stereo cameras advance low cloud science. ALI and SHOW provide information for the important upper-troposphere/lower-stratosphere (UTLS) region. Lidar UV channel aids the characterization of aerosol absorption and discrimination of anthropogenic aerosols.

Applications Narrative

Factors that Enhance Applications

The 3-wavelength lidar will provide estimates of aerosol size (e.g., PM1, PM2.5) and type (e.g., dust, smoke). Health studies and AQ models would benefit from accurate measurements of extinction profiles, leading to improved aerosol sizes/types.

The wide swath radar is important for gridded precipitation to support Water Resources applications and NWP improvements to CCP Modeling & Forecasting.

Stereo cameras will provide information on smoke and volcanic plume heights, which are critical for accurate monitoring and forecasting.

Opportunities to Further Enable Applications

The addition of an inclined orbit would provide more sampling to:

- **Capture diurnal aerosol observations** that will improve the reliability of AQ monitoring & forecasting.
- **Resolve diurnal convective cycle** that will greatly expand the benefit to support Water Resources, Weather, and Climate applications.
- **Enable radiometer cross-calibration with the POR** to benefit Water Resources and CCP applications.

Higher spatial resolution (5-10 km) and lower frequency radiometer channels (89 GHz) would enhance gridded precipitation to support Water Resources applications and precipitation characterization for CCP applications.

Programmatic Narrative

Pros:

- **This architecture maximizes the extent to which international contributions are utilized and is truly a multi-national collaboration with proven and trusted partners.**
- The CSA instrument's smaller Size, Weight and Power are less costly to accommdate. The Aerosol Limb Sounder (ALI) and Water Vapor Sensor (SHOW) are de-scopable providing enhancing capability if there are development issues. The Spectrometer (Spec03) is not de-scopable, however, it is not high risk and saves the US cost by providing minimum capability it would otherwise bear full cost for.

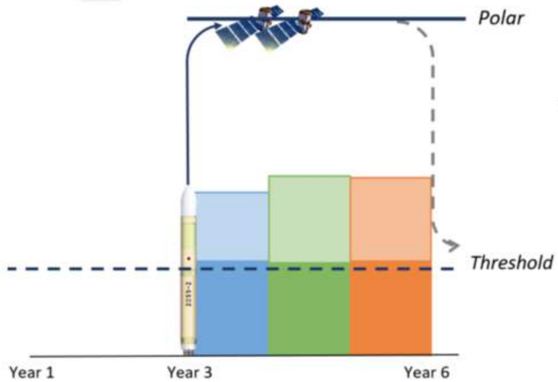
Cons:

- Lidar 06 (CNES): Accommodating the UV capability within the already complex US High Spectral Resolution Lidar (HSRL) adds cost and risk to the delivery of the most expensive and complex ACCP instrument for significantly enhancing capability. The UV capability is moderately de-scopable should issues arise.
- Radar 17 (JAXA): Accommodating the very large JAXA radar (~400kg/600W) which provides Ku Band Dopper with Wide Swath, even with a contributed LV, drives the SSP-2 Spacecraft to be large and expensive.
- **Lidar 06 and Radar 17 drive a single launch/single orbit plane to stay within the cost target increasing program complexity, decreasing flexibility and deferring ACCP Science until the full system can be developed and launched together (2031 dependent upon funding profile).**
- **There is some likelihood that de-scope option(s) may need to be executed in Pre-Phase A / Phase A to stay within cost target.**

Architecture P1

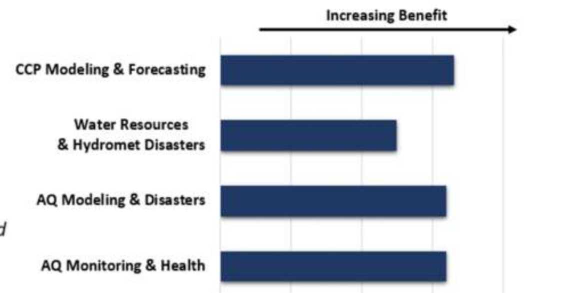
Science Benefit

Q1 – Convective Storm Processes
Q2 – Air Pollution and Distribution
Q3 – Climate Sensitivity and Feedback
(Baseline Science/ Enhanced Science)



Applications Benefit

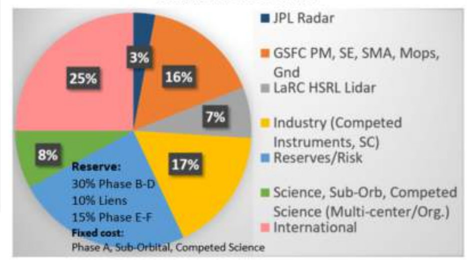
CCP Modeling & Forecasting: S2S, NWP, Climate, Tropical Cyclone Forecasts
Water Resources & Hydromet Disasters: Agriculture, Hydro-modeling, Extreme Events/Disasters, Insurance, Transportation
AQ & Disasters: AQ Modeling, Fires, Volcanoes, Dust Storms
AQ & Health: Rules and Regulation, Health/Insurance, Air Pollution



Programmatic Factors

Programmatic Factors	Rank
Continuity of Observations	2nd
Innovative Mission Implementation	2nd
Transformative Science	2nd
Flexibility with Funding Profiles	3rd
Flight Project Schedule Risk	3rd
Number of International Partners: 3	
Cross-benefit with Other Disciplines: Oceans	

Distribution of Work



WBS Element

WBS Element		Cost ($M)
Phase A	$	39.1
Phase B-D		
1.0 Project Management	$	77.6
2.0 Systems Engineering	$	44.5
3.0 Safety & Mission Assurance	$	51.7
4.0 Science & Technology	$	103.5
5.0 Payloads	$	749.1
6.0 Spacecraft	$	285.4
7.0/9.0 Mission Operations/Ground Systems	$	82.5
8.0 Launch Vehicle / Services	$	-
10.0 Systems Integration & Testing	$	51.7
Phase E-F	$	81.0
Sub-Orbital	$	29.3
Competed Science	$	48.9
30% Reserve Phase B-D/15% Phase E	$	446.8
Encumbered Risk	$	100.3
Total (minus contributions)	**$**	**1,598**

Note: All costs in FY18 dollars, reported at ~50% confidence level

Risk

Liens/Encumbrances FY18 ($100.3M)

Lidar06	$37.9	Radio07	$3.7	SHOW	$1.7
Radar17	$26.1	Polar04b/07	$3.2		
Spec03	$13.8	Spec04	$4.7		
Radar13E	$7.3	ALI	$1.8		

Top 10 Risks/Threats

Risk #	Type	Risk Title	Likelihood	Consequence	LxC
Lidar06	P	Risk of Growth (Mass, Power, Footprint)	4	5	20
Radar13E	P	Risk of Remaining Technology Dev.	4	5	20
Lidar06	T	UV Transmitter On-Orbit Degradation	3	5	15
Arch-1	T	Risk of Single Launch	2	5	10
Radar13E	P	Risk of Pre-Launch Technical Issue(s)	3	3	9
Lidar06	P	Risk of Pre-Launch Technical Issue(s)	4	2	8
Spec04	P	Risk of Science Algorithm Dev.	4	2	8
Camera	P	Risk of Growth (Mass, Power, Footprint)	4	2	8
Camera	P	Risk of Science Algorithm Dev.	4	2	8
ALI/SHOW	P	Risk of Science Algorithm Dev.	4	2	8

P=Programmatic w/Cost Consequence (2=2-5%; 3=5-7%; 4=7-10%; 5=>10%); T=Technical

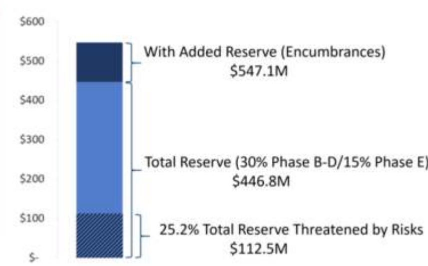
Descope Options (Cumulative) ($M)

1. **Descope ALI/SHOW ($1,556M)** *Loss of information for the important upper-troposphere/lower-stratosphere (UTLS) region and extreme volcanic/smoke events and their relation to vertical transport by convection.*

2. **Descope Camera Δt ($1,529M)** *Loss of information on clouds and plume top evolution.*

3. **Lidar05 in lieu of Lidar06 ($1,456M)** *Loss of lidar UV channel degrades the characterization of aerosol properties, including absorption.*

Reserves



Instrumentation Highlights

Radar13E+1
W-Band Doppler, Nadir; Ka-Band Doppler; Ku-Band Doppler; 15km Swath

Radio07
118, 183, 240, 310, 380, 660, 880 GHz, 750km Swath

Lidar06
355nm & 532nm HSRL, 1064nm Backscatter

Polar07
Multi-angle, UV-SWIR, 550km Swath, 0.5km FOV

Spec03
LWIR, FIR, 400km Swath

Spec04
UV, VIS, NIR, SWIR, 200km Swath

Camera
Tandem Stereo Camera Visible Imaging

ALI
Aerosol Limb Sounder

SHOW
Water Vapor Limb Sounder

Polar = Polarimeter Radio = Radiometer Spec = Spectrometer

Science Narrative

Convective Storm Processes

Pros: Transformative capabilities for measuring vertical motions in shallow to deep convection. Measurements span light to heavy precipitation with 3 coincident frequencies. **Cons:** Lack of Ku radar swath degrades ability to characterize 3D structure and provide feature context. Radiometer footprints are large for convective studies. Lack of inclined orbit is detrimental to characterization of sub-daily convective processes.

Air Pollution and Distribution

Pros: Lidar, polarimeter, radar combination provides unprecedented particulate characterization and information on aerosol removal/redistribution in light to heavy precipitation. Tandem stereo cameras add information on plume top evolution, while ALI provides information on extreme volcanic/smoke events and their relation to vertical transport by convection. Lidar UV channel enables better characterization of aerosol type, size, absorption, concentration. **Cons:** Lack of radar swath degrades ability to characterize precipitation and its impacts on aerosol wet removal. Lack of inclined orbit is detrimental to characterization of sub-daily aerosol processes.

Climate Sensitivity and Feedback

Pros: Provides broad diversity of measurements for low and high cloud feedback, direct and indirect aerosol radiative effects, and cold cloud processes. Radar profiling to near surface and cameras offer significant advances for low clouds and snowfall. ALI and SHOW provide information for the important upper troposphere/lower stratosphere (UTLS) region. Lidar UV channel aids the characterization of aerosol absorption and discrimination of anthropogenic aerosols. **Cons:** Lack of radar swath degrades ability to relate convective properties to high clouds.

Applications Narrative

Factors that Enhance Applications

The 3-wavelength lidar will provide estimates of aerosol size (e.g., PM1, PM2.5) and type (e.g., dust, smoke). Health studies and AQ models would benefit from accurate measurements of extinction profiles, leading to improved aerosol sizes/types.

Coincident 3-frequency Ku/Ka/W Doppler radar observations are very desirable for CCP model development, providing vertical velocity and hydrometeor details.

Stereo cameras will provide information on smoke and volcanic plume heights, which are critical for accurate monitoring and forecasting.

Opportunities to Further Enable Applications

The addition of an inclined orbit would provide more sampling to:

- **Capture diurnal aerosol observations** that will improve the reliability of AQ monitoring & forecasting.
- **Resolve diurnal convective cycle** that will greatly expand the benefit to support Water Resources, Weather, and Climate applications.
- **Enable radiometer cross-calibration with the POR** to benefit Water Resources and CCP applications.

Inclusion of a wider swath radar and higher spatial resolution (5-10 km) and lower frequency radiometer channels (89 GHz) will improve gridded precipitation for Water Resources applications and precipitation characterization for CCP Modeling & Forecasting.

Programmatic Narrative

Pros:

- **This architecture utilizes a single Radar for Ku, Ka and W Band Doppler, giving up Ku band Swath, to reduce overall Size, Weight and Power to reduce the cost of P1.**
- **This architecture has the lowest overall cost. Because this architecture has the lowest overall cost, there is less likelihood that de-scope option(s) may need to be executed in Pre-Phase A / Phase A to stay within cost target.**
- The CSA instruments' smaller Size, Weight and Power are less costly to accommodate. The Aerosol Limb Sounder (ALI) and Water Vapor Sensor (SHOW) are de-scopable providing enhancing capability if there are development issues. The Spectrometer (Spec03) is not de-scopable, however, it is not high risk and saves the US cost by providing minimum capability it would otherwise bear full cost for.

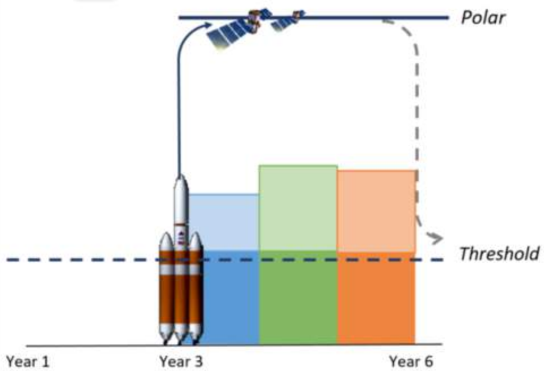
Cons:

- Lidar 06 (CNES): Accommodating the UV capability within the already complex US High Spectral Resolution Lidar (HSRL) adds cost and risk to the delivery of the most expensive and complex ACCP instrument for significantly enhancing capability. The UV capability is moderately de-scopable should issues arise.
- **Lidar 06 and Radar 13E+1 cost drive a single launch/single orbit plane to stay within the cost target deferring ACCP Science until the full system can be developed and launched together (2031 dependent upon funding profile).**

Architecture P2

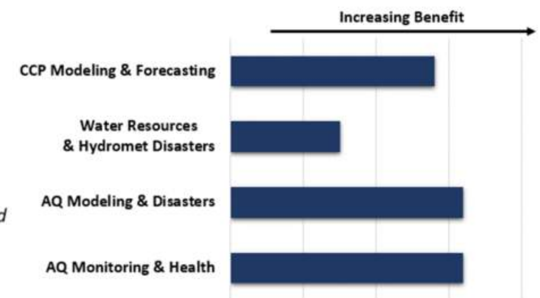
Science Benefit

Q1 – Convective Storm Processes
Q2 – Air Pollution and Distribution
Q3 – Climate Sensitivity and Feedback
(Baseline Science/ Enhanced Science)



Applications Benefit

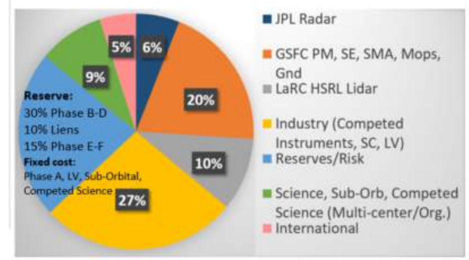
CCP Modeling & Forecasting: S2S, NWP, Climate, Tropical Cyclone Forecasts
Water Resources & Hydromet Disasters: Agriculture, Hydro-modeling, Extreme Events/Disasters, Insurance, Transportation
AQ & Disasters: AQ Modeling, Fires, Volcanoes, Dust Storms
AQ & Health: Rules and Regulation, Health/Insurance, Air Pollution



Programmatic Factors

Programmatic Factors	Rank
Continuity of Observations	3rd
Innovative Mission Implementation	2nd
Transformative Science	3rd
Flexibility with Funding Profiles	2nd
Flight Project Schedule Risk	2nd
Number of International Partners: 2	
Cross-benefit with Other Disciplines: Oceans	

Distribution of Work



WBS Element

WBS Element		Cost ($M)
Phase A	$	39.1
Phase B-D		
1.0 Project Management	$	44.9
2.0 Systems Engineering	$	25.7
3.0 Safety & Mission Assurance	$	29.9
4.0 Science & Technology	$	59.8
5.0 Payloads	$	386.4
6.0 Spacecraft	$	211.8
7.0/9.0 Mission Operations/Ground Systems	$	82.5
8.0 Launch Vehicle / Services	$	107.5
10.0 Systems Integration & Testing	$	29.9
Phase E-F	$	81.0
Sub-Orbital	$	29.3
Competed Science	$	48.9
30% Reserve Phase B-D/15% Phase E	$	273.4
Encumbered Risk	$	76.3
Total (minus contributions)	**$**	**1,432.0**

Note: All costs in FY18 dollars, reported at ~50% confidence level

Risk

Liens/Encumbrances FY18 ($76.3M)

Lidar06	$37.9	Polar04b/07	$3.2
Spec03	$13.8	Spec04	$4.7
Radar13E+1	$9.5	ALI	$1.8
Radio07	$3.7	SHOW	$1.7

Top 10 Risks/Threats

Risk #	Type	Risk Title	Likelihood	Consequence	LxC
Lidar06	P	Risk of Growth (Mass, Power, Footprint)	4	5	20
Radar13E+1	P	Risk of Remaining Technology Dev.	4	5	20
Radar13E+1	P	Risk of Pre-Launch Technical Issue(s)	4	4	16
Lidar06	T	UV Transmitter On-Orbit Degradation	3	5	15
Arch-1	T	Risk of Single Launch	2	5	10
Lidar06	P	Risk of Pre-Launch Technical Issue(s)	4	2	8
Spec04	P	Risk of Science Algorithm Dev.	4	2	8
Camera	P	Risk of Growth (Mass, Power, Footprint)	4	2	8
Camera	P	Risk of Science Algorithm Dev.	4	2	8
ALI/SHOW	P	Risk of Science Algorithm Dev.	4	2	8

P=Programmatic w/Cost Consequence (2=2-5%; 3=5-7%; 4=7-10%; 5=>10%); T=Technical

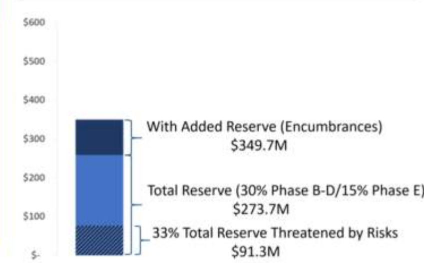
Descope Options (Cumulative) ($M)

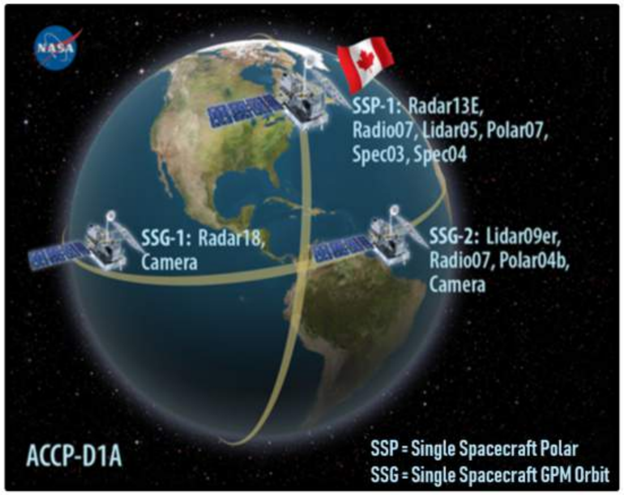
1. Descope ALI/SHOW ($1,334M) *Loss of information for the important upper-troposphere/lower-stratosphere (UTLS) region and extreme volcanic/smoke events and their relation to vertical transport by convection.*

2. Descope Camera Δt ($1,262M) *Loss of information on clouds and plume top evolution.*

3. Lidar05 in lieu of Lidar06 ($1,217M) *Loss of lidar UV channel degrades the characterization of aerosol properties, including absorption.*

Reserves





Instrumentation Highlights

Radar13E
W-Band Doppler, Nadir; Ka-Band Doppler; 15km Swath

Radar18
W-Band Doppler, Ku-Band Doppler

Radio07
118, 183, 240, 310, 380, 660, 880 GHz, 750km Swath

Lidar05
532nm HSRL, 1064nm Backscatter

Lidar09er
532nm, 1064nm Backscatter

Polar07
Multi-angle, UV-SWIR, 550km Swath, 0.5km FOV

Polar04b
Multi-angle, UV-SWIR, 1130km Swath, 1 km FOV

Spec03
LWIR, FIR, 400km Swath

Spec04
UV, VIS, NIR, SWIR, 200km Swath

Camera
Tandem Stereo Camera Visible Imaging

Polar = Polarimeter Radio = Radiometer Spec = Spectrometer

Science Narrative

Convective Storm Processes

Pros: Transformative measurement of diurnally varying vertical motions in shallow to deep convection, spanning light to heavy precipitation, in inclined orbit. Additional measurements in polar orbit for weak convection/upper levels of strong convection.
Cons: Narrow Ku radar swath degrades ability to provide feature context. Radiometer footprints are large for convective studies.

Air Pollution and Distribution

Pros: Particulate characterization and aerosol removal/redistribution in light to heavy precipitation is well served by the lidar, polarimeter and radar combination. HSRL Lidar in polar orbit provides unprecedented characterization of near-surface pollutants. Tandem stereo cameras add information on plume top evolution, while lidar/polarimeter measurements in inclined orbit provides information on sub-daily aerosol processes. **Cons:** Loss of lidar UV channel negatively impacts the characterization of aerosol properties. Lack of radar swath degrades ability to characterize precipitation and its impacts on aerosol wet removal.

Climate Sensitivity and Feedback

Pros: Provides key measurements for low and high cloud feedback, direct and indirect aerosol radiative effects, and cold cloud process studies. Radar profiling to near surface and cameras offer significant advances for low clouds and snowfall. **Cons:** Lack of radar swath degrades ability to relate convective properties to high clouds. Loss of lidar UV channel degrades characterization of aerosol absorption, and the ability to get consistent climate record for cloud feedback.

Applications Narrative

Factors that Enhance Applications

Inclined orbit enhances coverage and sampling opportunities, affecting the observations of high impact A and CCP phenomena.

Combined Lidar/Polarimeter in both polar and inclined orbit supports AQ modeling/monitoring centers need for increased sampling and diurnal aerosol observations to improve the reliability of AQ monitoring and forecasting.

Combined Radar/Radiometer observations in the inclined orbit allow for cross-calibration with the POR to derive gridded precipitation products to support Water Resources and CCP applications.

Ku/W-band Doppler Radar observations capture diurnal precipitation rates and convection to support NWP, aviation, and tropical cyclone centers to improve modeling and forecasting.

Stereo cameras will provide information on smoke and volcanic plume heights, which are critical for accurate monitoring and forecasting.

Opportunities to Further Enable Applications

The addition of a UV wavelength (355 nm) to the lidar will enable estimates of PM1 and PM2.5, and more accurate aerosol types (e.g., dust, smoke) for Health and AQ applications.

Inclusion of a wider swath radar and higher spatial resolution (5-10 km) and lower frequency radiometer channels (89 GHz) will improve gridded precipitation for Water Resources applications and precipitation characterization for CCP Modeling & Forecasting.

Programmatic Narrative

Pros:

- **Path for Early Science, first launch in 2027-2028 leading to a significant response to the 2017 Decadal Survey report.**
- **Highest ranked for transformative science and application opportunities.**
- **Enhanced sampling benefits enabled from distributed constellation of SmallSats.**
- **Significant Industry-Hosted Payload capability to reduce cost and enable first launch segment.**
- **Large opportunity for industry involvement; NASA multi-center participation consistent with Tier/Core Competency priorities.**
- Due to the wide range of costs for Hosted-Payload opportunities there may be flexibility in Pre-Phase A/Phase A after RFI submittals and partner identification to execute 1 or more opportunities on the opportunities list, in consultation with HQ, for this Architecture.

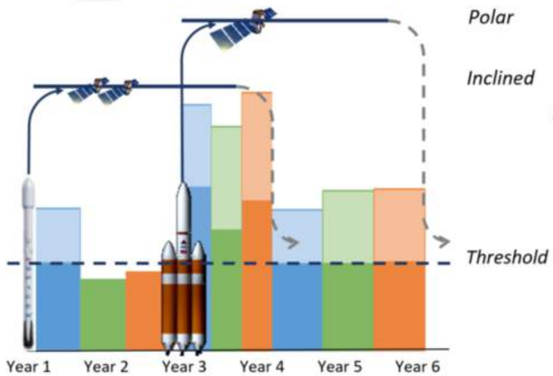
Cons:

- **Minimal International participation; it does not accommodate contributions of a wide swath doppler radar from JAXA, UV lidar detector from CNES, or the ALI and SHOW limb instruments from CSA within the cost target.**
- Funding profile within total cost guidance, with the initial funding wedge >$200M lower than originally planned, but with second wedge requiring additional funds for the second launch in 2029-2031 to meet Threshold Science needs for ACCP.

Architecture D1A

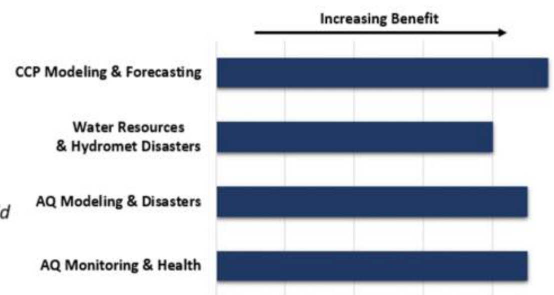
Science Benefit

Q1 – Convective Storm Processes
Q2 – Air Pollution and Distribution
Q3 – Climate Sensitivity and Feedback
(Baseline Science/ Enhanced Science)



Applications Benefit

CCP Modeling & Forecasting: S2S, NWP, Climate, Tropical Cyclone Forecasts
Water Resources & Hydromet Disasters: Agriculture, Hydro-modeling, Extreme Events/Disasters, Insurance, Transportation
AQ & Disasters: AQ Modeling, Fires, Volcanoes, Dust Storms
AQ & Health: Rules and Regulation, Health/Insurance, Air Pollution

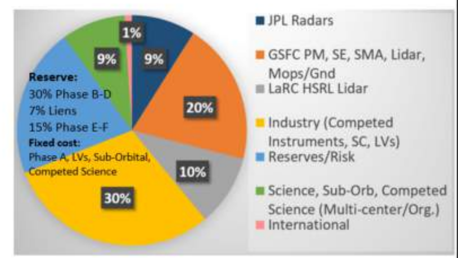


Programmatic Factors

Programmatic Factors	Rank
Continuity of Observations	1st
Innovative Mission Implementation	1st
Transformative Science	1st
Flexibility with Funding Profiles	1st
Flight Project Schedule Risk	1st

Number of International Partners: 1
Cross-benefit with Other Disciplines: Hydroglogy, Oceans

Distribution of Work



WBS Element

WBS Element		Cost ($M)
Phase A	$	39.1
Phase B-D		
1.0 Project Management	$	47.5
2.0 Systems Engineering	$	27.2
3.0 Safety & Mission Assurance	$	31.7
4.0 Science & Technology	$	63.3
5.0 Payloads	$	423.5
6.0 Spacecraft	$	209.6
7.0/9.0 Mission Operations/Ground Systems	$	75.0
8.0 Launch Vehicle / Services	$	166.2
10.0 Systems Integration & Testing	$	31.7
Phase E-F	$	65.4
Sub-Orbital	$	29.3
Competed Science	$	48.9
30% Reserve Phase B-D/15% Phase E	$	282.6
Encumbered Risk	$	59.8
Total (minus contributions)	**$**	**1,586.0**

Note: All costs in FY18 dollars, reported at ~50% confidence level

Risk

Liens/Encumbrances FY18 ($59.8M)

Spec03	$13.8	Radio07	$3.7
Lidar05	$12.9	Polar04b/07	$6.5
Radar 18	$10.9	Spec04	$4.7
Radar13E	$7.3		

Top 10 Risks/Threats

Risk #	Type	Risk Title	Likelihood	Consequence	LxC
Lidar05	P	Risk of Growth (Mass, Power, Footprint)	4	5	20
Radar13E	P	Risk of Remaining Technology Dev.	4	5	20
Lidar09r	P	Risk of Growth (Mass, Power, Footprint)	2	5	10
Radar18	P	Risk of Pre-Launch Technical Issue(s)	3	3	9
Radar13E	P	Risk of Pre-Launch Technical Issue(s)	3	3	9
Lidar09r	P	Risk of Manufacturability Issues	3	3	9
Lidar05	P	Risk of Remaining Technology/Engineering Dev.	4	2	8
Lidar05	P	Risk of Pre-Launch Technical Issue(s)	4	2	8
Spec04	P	Risk of Science Algorithm Dev.	4	2	8
Camera	P	Risk of Growth (Mass, Power, Footprint)	4	2	8

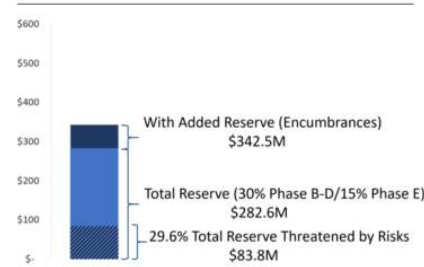
P=Programmatic w/Cost Consequence (2=2-5%; 3=5-7%; 4=7-10%; 5=>10%); T=Technical

Descope Options (Cumulative) ($M)

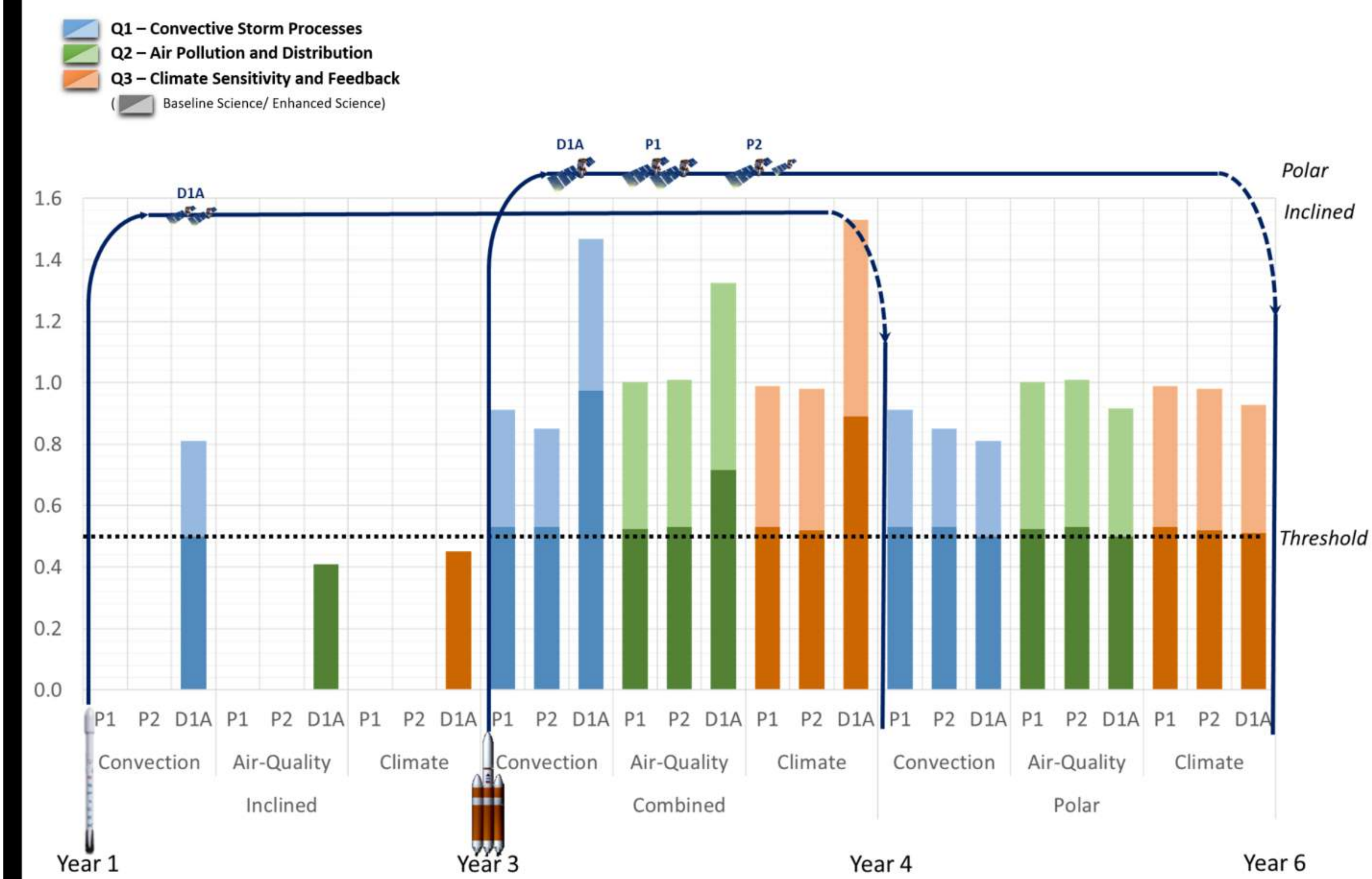
1. **Descope Camera Δt ($1,530M)** *Loss of information on clouds and plume top evolution.*

2. **Radar12 in lieu of Radar18 ($1,497M)** *Loss of information about vertical motions and precipitation rates in heavy rainfall events.*

Reserves



Comparison of Science Benefit



Appendix C—ACCP Science Teams

C.1 Science and Applications Leadership Team

Howard Barker, Environment and Climate Change Canada
Emily Berndt, MSFC
Scott Braun, GSFC
Helene Brogniez, LATMOS/Univ. UVSQ
Greg Carmichael, Univ. Iowa
Marjolaine Chiriaco, LATMOS/University UVSQ
Jason Cole, Environment and Climate Change Canada
Juan Cuesta, LISA/University of UPEC
Arlindo da Silva, GSFC
Richard Ferrare, LaRC
Meloë Kacenelenbogen, ARC
Dalia Kirschbaum, GSFC
Jay Mace, U. Utah
Vincent Noël, LA/CNRS
Riko Oki, JAXA
Ali Omar, LaRC
Walter Petersen, MSFC
Jens Redemann, U. Okla.
Graeme Stephens, JPL
Yukari Takayabu, U. Tokyo
Sue van den Heever, CSU
Duane Waliser, JPL
David Winker, LaRC

C.2 Science Impact Teams—Aerosols

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Adam Bourassa, Univ. of Saskatchewan
Sharon Burton, LaRC
Brian Cairns, GISS
Patricia Castellanos, GSFC
Eduard Chemyakin, LaRC
Marjolaine Chiriaco, IPSL
Pete Colarco, GSFC
Flavien Cornut, CNRM
Juan Cuesta, LISA/Univ. of UPEC
Oleg Dubovik, LOA/CNRS
Laaziz El Amraoui, CNRM
Reed Espinosa, GSFC
Connor Flynn, U. Okla.
Lan Gao, U. Okla.
Michael Garay, JPL

Robert Holz, U. Wisc.
Olga Kalashnikova, JPL
Seiji Kato, LaRC
Osku Kemppinen, GSFC
Rob Levy, GSFC
Xu Liu, LaRC
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Richard Moore, LaRC
Tomoaki Nishizawa, NIES-Japan
Ed Nowottnick, GSFC
David Painemal, LaRC
Kathleen Powell, LaRC
Roseline Schmisser, CNES
Snorre Stamnes, LaRC
Tyler Thorsen, LaRC
Travis Toth, LaRC
Solene Turquety, LMD
Mark Vaughan, LaRC
Feng Xu, JPL
John Yorks, GSFC

C.3 Science Impact Teams—CCP

Team lead: Jay Mace, U. Utah
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Dominique Bouniol, CNRM/CNRS
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Laura Hermozo, CNES
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Pavlos Kollias, Stonybrook
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Matt Lebsock, JPL
Yuli Liu, U. Utah
Kerry Meyer, GSFC
Dan Miller, USRA

Masashi Minamide, JPL
Richard Moore, LaRC
Joe Munchak, GSFC
Vincent Noël, LA/CNRS
Hajime Okamoto, Kyushu University
David Painemal, LaRC
Derek Posselt, JPL
Roseline Schmisser, CNES
Rick Schulte, Colo. St. Univ.
Shoichi Shige, Kyoto University
Snorre Stamnes, LaRC
Rachel Storer, JPL
Ousmane Sy, JPL
Nobuhiro Takahashi, Nagoya University
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Mark Vaughan, LaRC
Zhuocan Xu, U. Utah
John Yorks, GSFC

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Patrick Gatlin, MSFC
Svetla Hristova-Veleva, JPL
Yasutaka Ikuta, JMA
Olga Kalashnikova, JPL
Takuji Kubota, JAXA
Anita Leroy, MSFC
Aaron Naeger, MSFC
Ali Omar, LaRC
Andrea Portier, GSFC
Danahe Raquin-Ricard, Environment and Climate Change Canada
Amber Soja, LaRC
Solène Turquety, LMD/University of Sorbonne

C.5 Science Community Committee
Team co-lead: Greg Carmichael, Univ. Iowa
Team co-lead: Sue van den Heever, CSU
Ana Barros, Duke
Helene Chepfer, LMD/University of Sorbonne
Andy Dessler, Texas A&M
Graham Feingold, NOAA

Mike Fromm, NRL
Andrew Gettleman, NCAR
Colette Heald, MIT
Yi Huang, McGill University
Olivier Jourdan, LAMP/University of Clermont Ferrand
Steve Klein, LLNL
Mark Kulie, NOAA
Tristan L'Ecuyer, Univ. Wisconsin
Jean-François Léon, LA/CNRS
Ruby Leung, PNNL
Yang Liu, Emory
Johnny Luo, CCNY
Hirohiko Masunaga, Nagoya University
Allison McComiskey, DOE/BNL
James Nelson, NOAA/NWS/WPC
Steve Nesbitt, Univ. Illinois Urbana-Champaign
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Acronyms

3MI	Multi-viewing, Multi-channel, Multi-polarization Imager
A	Aerosols
AAOD	Abosrption Aerosol optical depth
ABI	Advanced Baseline Imager
ACCP	Aerosol, Clouds, Convection, and Precipitation
ACW	Architecture Construction Workshop
AHI	Advanced Himawari Imager
AIT	Applications Impact Team
ALI	Aerosol Limb Imager
AMI	Advanced Meteorological Imager
AMSR-E	Advanced Microwave Scanning Radiometer for EOS
AMSU	Advanced Microwave Sounding Unit
AOD	Aerosol optical depth
AQ	Air Quality
AQI	Air Quality Index
AR	Assessment Report
ARF	Aerosol Radiative Forcing
ARM	Atmospheric Radiation Measurement
ATLID	ATmospheric LIDar
ATMS	Advanced Technology Microwave Sounder
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation
CAR	Community Assessment Report
CATS	Cloud-Aerosol Transport System
CCN	Cloud Condensation Nuclei
CCP	Clouds, Convection, and Precipitation
CDC	Collaborative Design Center
CDI	Cloud Dynamics Imager
CDOM	Color Dissolved Organic Matter
CDR	Climate Data Record
CERES	Clouds and the Earth's Radiant Energy System
CESM	Community Earth System Model
CFAD	Contoured frequency by altitude diagram
CGMS	Coordination Group for Meteorological Satellites
CMIP	Coupled Model Intercomparison Project
CNES	Centre National d'Etudes Spatiales
CoSMIR	Conical Scanning Millimeter-wave Imaging Radiometer
CPL	Cloud Physics Laboratory
CPR	Cloud Profiling Radar
CRE	Cloud radiative effect
CrIS	Cross-track Infrared Sounder
CSA	Canadian Space Agency
DLR	German Aerospace Center
DO	Designated Observable
DoD	Department of Defense

DOE	Department of Energy
DPCA	Displaced Phased Center Antenna
DRE	Direct Radiative Effects
DRS	Direct Retrieval Simulations
DS	Decadal Survey
ECS	Equilibrium Climate Sensitivity
EOS	Earth Observing System
EPA	Environmental Protection Agency
ERF	Effective Radiative Forcing
ESA	European Space Agency
ESD	Earth Science Division
ESDS	Earth Science Data System
EU	European Union
EVS	Earth Venture Suborbital
FAA	Federal Aviation Administration
FCI	Flexible Combined Imager
FEMA	Federal Emergency Management Agency
FIR	Far Infrared
GCM	Global climate model
GCOS	Global Climate Observing System
GEMS	Geostationary Environment Monitoring Spectrometer
GEO	Geostationary
GEWEX	Global Energy and Water Exchanges
GISS	Goddard Institute for Space Studies
GLM	Geostationary Lightning Mapper
GMAO	Global Modeling and Assimilation Office
GMI	GPM MIcrowave Imager
GOES	Geostationary Operational Environmental Satellite
GPM	Global Precipitation Measurement
GSFC	Goddard Space Flight Center
GV	Geophysical Variable
HARP	Hyper-Angular Rainbow Polarimeter
HQ	Headquarters
HSB	Humidity Sounder for Brazil
HSRL	High spectral resolution lidar
HWIC	High Ice Water Content
IASI	Infrared Atmospheric Sounding Interferometer
ICA	Information Content Analysis
ICI	Ice Cloud Imager
IPCC	Intergovernmental Panel on Climate Change
IR	Infrared
ISCCP	International Satellite Cloud Climatology Project
ISCCP-NG	International Satellite Cloud Climatology Project – Next Generation
ISS	International Space Station
IVAV	In-cloud Vertical Air Velocity
IWP	Ice Water Path

JAXA	Japanese Exploration Agency
JPL	Jet Propulsion Laboratory
JPSS	Joint Polar Satellite System
LaRC	Langley Research Center
LEO	Low Earth Orbit
LES	Large Eddy Simulation
LMIC	Low-and-Middle Income Countries
LW	Longwave
LWG	Lidar Working Group
LWIR	Longwave Infrared
LWP	Liquid water path
MAIA	Multi-Angle Imager for Aerosols
MCMC	Markov Chain Monte Carlo
MCS	Mesoscale Convective System
MEE	Mass Extinction Efficiency
METOP SG	Meteorological Operational satellite Second Generation
MF	Multi-frequency
MI	Most Important
MISR	Multi-angle Imaging SpectroRadiometer
MODIS	Moderate Resolution Imaging Spectroradiometer
MRMS	Multi-Radar Multi-Sensor
MW	Microwave
MWI	Microwave Imager
MWS	Microwave Sounder
NAAQS	National Ambient Air Quality Standards
NGO	Non-Government Organization
NIR	Near infrared
NUBF	Non-Uniform Beam Filling
NWP	Numerical Weather Prediction
O	Objective
OCI	Ocean Color Instrument
OE	Optimal Estimation
OECD	Organisation for Economic Co-operation and Development
OMI	Ozone Monitoring Instrument
OMPS	Ozone Monitoring and Profiler Suite
OSSE	Observing System Simulation Experiment
OTB	Orbital Test Bed
PACE	Plankton, Aerosol, Cloud, ocean Ecosystem
PARASOL	Polarization and Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations from a Lidar
PBL	Planetary Boundary Layer
PDF	Probability distribution function
PM	Particulate Matter
POLDER	Polarization and directionality of Earth reflectances
PoR	Program of record
QS	Quality Score

RDA	Real Data Analysis
RDF	Radar Detection Fraction
RFI	Request For Information
RMSE	Root Mean Square Error
S2S	Subseasonal-to-Seasonal
SALT	Science and Applications Leadership Team
SAPHIR	Sounder for Probing Vertical Profiles of Humidity
SATM	Science and Applications Traceability Matrix
SCC	Science Community Committee
SET	Systems Engineering Team
SIT	Science Impact Team
SLF	Supercooled liquid fraction
SLW	Supercooled liquid water
SMT	Science Management Team
SNR	Signal to Noise Ratio
SO	Suborbital
SODA	Synergized Optical Depth of Aerosols
SOWG	Suborbital Working Group
SPA	Statistical Performance Analysis
SSA	Single Scatter Albedo
SSMI	Special Sensor Microwave Imager
SW	Shortwave
SWCRE	Shortwave Cloud Radiative Effects
Tb	Brightness temperature
TC	Total atmospheric Column
TCWV	Total Column Water Vapor
TEMPO	Tropospheric Emissions: Monitoring Pollution
TMI	TRMM Microwave Imager
TOA	Top of the atmosphere
TOMS	Total Ozone Mapping Spectrometer
TRL	Technology Readiness Level
TRMM	Tropical Rainfall Measuring Mission
TWICE	Tropospheric Water and cloud ICE
USGS	U.S. Geological Survey
UTLS	Upper Troposphere Lower Stratosphere
UV	Ultraviolet
UVNS	Ultra-violet, Visible and Near-infrared Sounder
VIIRS	Visible Infrared Imaging Radiometer Suite
VIS	Visible
VP	Vertical Profile
VSWIR	Visible Shortwave Infrared
WCRP	World Climate Research Programme
WHO	World Health Organization
WSF	Weather System Follow-on